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SECOND QUARTERLY REPORT
DESIGN STUDY
FOR
LUNAR EXPLORATION HAND TOOLS

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ABSTRACT

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The purpose of this report is to present the results of the second three months work performed for the Design Study of Lunar Exploration Hand Tools, under NASA contract NAS 9-3647. A lunar surface geological task analysis was performed to determine the tool function requirements of the astronaut. A number of potential design approaches were considered, and various analyses were performed where required. A series of feasibility tests were conducted in order to evaluate the selected potential design approaches. In particular, potential interface problems between the space-suited astronaut and geological exploration tools were studied. Design approaches for most of the tools have been selected, and detail design and fabrication of these tools is currently in progress.

Author

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SUMMARY

A preliminary lunar surface geological task analysis was performed to define possible exploration traverses for the roving lunar astronaut, and to further define the anticipated tool requirements. It was recommended that six 30-degree sector traverses be performed in order to obtain a representative suite of geological samples. Each traverse would encompass a walking distance of approximately one mile. Twelve representative specimens, and twelve special interest specimens would be procured during each traverse.

As a result of the geological task analysis, several design approaches for the tool requirements were studied. The design approaches included the powered lunar geologists tool, sample weighing device, geological hand lens, and a surveying platform which would be integrated with the PLGT. The surveying platform will include provisions for horizontal leveling and angular measurements independent of the vertical position of the PLGT with tripod extended. Provisions were also included for a range and bearing measuring instrument such as an alidade, or a less sophisticated lensless stadiametric device.

Several preliminary feasibility tests were performed in order to evaluate the selected design approaches for the geological exploration tools. Drilling penetration rate evaluations of various types of coring bits were conducted for the PLGT. Evaluation of lens and lensless-type surveying instruments, PLGT mockup, sample weighing device, sample retriever, and geological hand lens was also performed in order to identify potential problem areas. Particular emphasis was placed on the evaluation of spacesuit-geological tool interface restrictions.

Design approaches for most of the tools have been selected, and the detail design and fabrication of these tools is in progress.

INTRODUCTION

The initial three month period of this Study consisted of an evaluation of the basic data influencing the design of the geological exploration hand tools. This included the lunar geological and environmental factors, human factors evaluation, and the Apollo LEM characteristics. As a result of the basic data evaluation, a potential design approach was selected for the PLGT and related auxiliary equipment. Preliminary operating parameters were established and detail design study requirements were defined. The results of this phase of the Study were presented in the First Quarterly Report.

The task analysis conducted during this report period permitted a more detailed definition of the exploration tool requirements. Subsequently, several design approaches were studied, and various feasibility tests were conducted in order to evaluate the selected approaches.

This report includes the work performed from January 26 through April 26, 1965, and was conducted under the auspices of Mr. M. B. Goldman, Manager of Logistic Support, Baltimore Division, Martin Company. Other individuals and their specialty areas, who are contributing to this program include:

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LUNAR SURFACE GEOLOGICAL TASK ANALYSIS AND TOOL REQUIREMENTS

General

A detailed geological task analysis is required in order to delineate the appropriate tools which will be needed by the lunar surface astronaut. This analysis must consider the maneuverability, dexterity and time limitations imposed upon the astronaut-geologist as guidelines for the tools selection. The final allocation of the astronaut's time on the lunar suface must also include the non-geological tasks such as vehicle checkout and inspection, emplacement of geophysical equipment, and the "sleep-eat" cycles. A more extensive mission analysis for all tasks to be performed by the LEM astronauts is being conducted by the U.S. Geological Survey.

Various operating criteria have been used as guidelines for the geological task analysis. These criteria are based upon the equipment and project goals which are currently planned for the early lunar missions, and are therefore subject to future revisions.

1. The landing sites selected for the early LEM missions will probably be featureless areas within the lunar maria.

2. A maximum of three, 3-hour lunar surface excursions will be made by each of the two LEM astronauts. At least one astronaut will remain within the LEM at all times except in the event of an emergency.

3. The astronauts will be restricted to a 1000-foot radius, 360 degree exploratory area surrounding the LEM.

4. The observations and measurements made by the roving astronaut will be voice transmitted to the LEM or earth for permanent recording.

Task Analysis Operations

The first task required of the astronaut is removal of the geological equipment from the LEM equipment bay. This task cannot be delineated in detail until the final equipment selection has been made and interfacing requirements with the LEM have been satisfied.

Difficulty in walking on the lunar surface and time limitations will probably not permit the astronaut outside of the LEM to perform more than the chief objectives of the investigation. These will include locating, extracting, describing and identifying, packaging and weighing the lunar surface materials. The operations will also include performing observations and measurements of structures, where and if these occur within the zone of investigation. The measurements and descriptions of the local terrain will be supplemented by a number of photographs taken by the roving astronaut with the hand-held lunar surface camera.

The astronaut will locate the sites of actual observations, sample extraction and measurements by use of a surveying instrument capable of range and azimuth determinations. If significant variations in lithologies are present in the investigated area, a geological map of the area can be made subsequently from the data gathered. The rock samples may be collected and measurements taken during a point-to-point traverse. The route traversed should be determined primarily by the astronaut and would depend on the actual nature of the lunar surface materials, specific spatial distribution of outcrops and topography. However, if the LEM lands on a surface of little or no relief as anticipated, a tentative scheme should be designed to insure that the astronaut obtains a representative suite of samples within the radius of investigation.

A tentative plan for obtaining the representative suite of lunar surface samples is illustrated in Figure 1. The plan is predicated upon six excursions, with each excursion incorporating a 30-degree sector of the 1000-foot radius circle of investigation. Samples would be procured at 200-foot intervals along the radii and periphery of the 30-degree sector, resulting in a total of 12 samples per traverse. If sufficient time is not available for six traverses, the sector area of the exploratory excursions must be increased or the total number of 30-degree sectors decreased. Deviations from the tentative plan may also be required if the terrain proves too difficult to traverse in certain areas or if more desirable sampling sites (outcrops, small craters, etc.) are observed off of the lines of traverse.

The straight line distance around the 30-degree traverse is 2,523 feet or approximately one-half mile. The total distance walked by the astronaut would probably be closer to one mile because of deviations to points of interest from the straight line traverse. Therefore, the three-hour, one mile traverse may be allocated in the following manner:

One Hour	-	Actual walking time, assuming a one mile per hour walking rate
One Hour	-	Total "stop" time at the 12 sample locations, assuming five minutes for procuring sample, performing measurements, and taking photographs
One Hour	-	Additional time for obtaining samples at other interesting locations
Three Hours	-	Total excursion time

Sample Location. The astronaut with his geological exploration equipment, will move from the LEM to the point of first sample collection. The position of this point (range and azimuth) should be determined relative to the LEM and

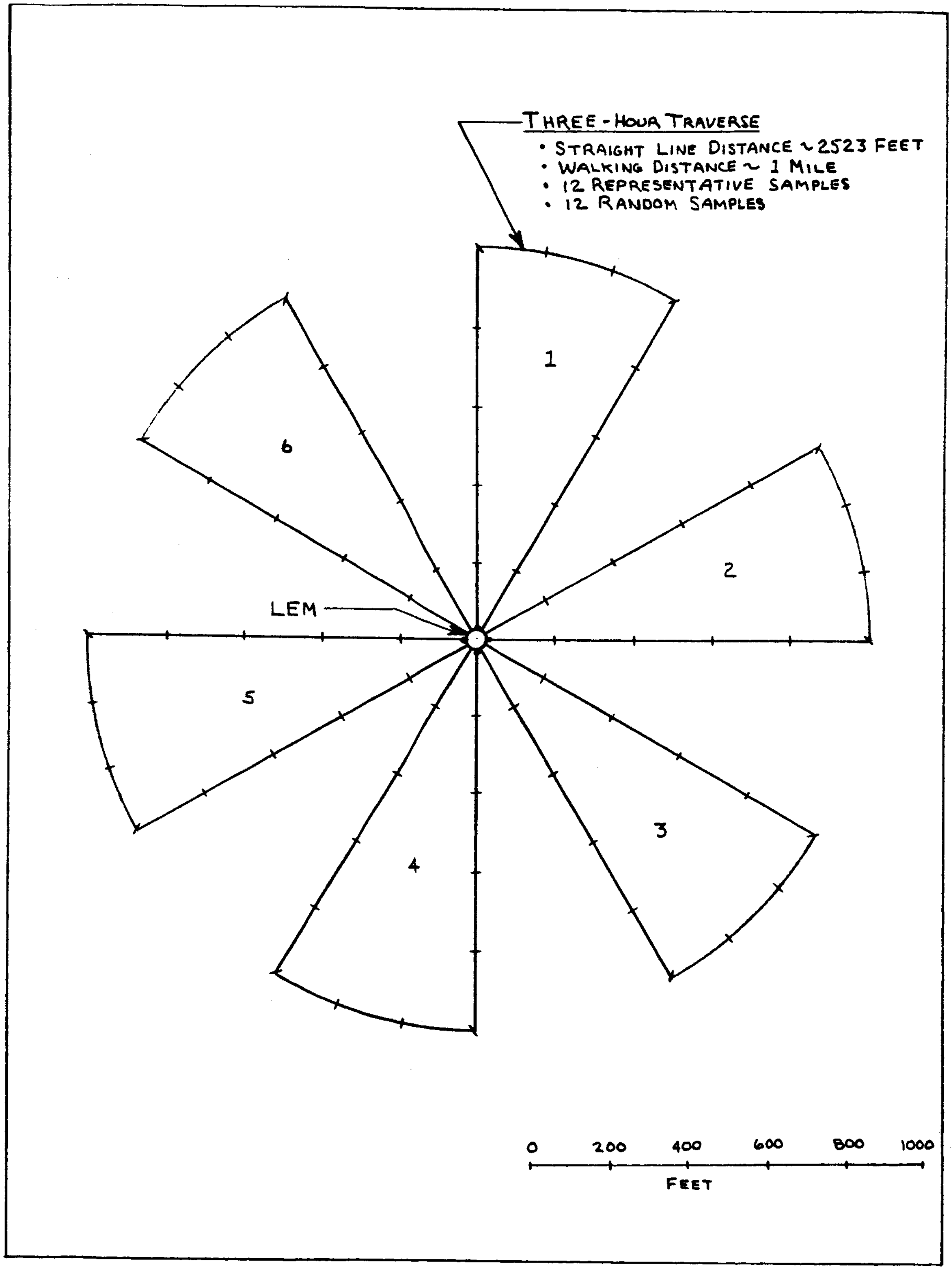

Figure 1. Lunar Surface Geological Sampling Plan

voice-transmitted to the LEM or earth for permanent recording. A non-magnetic compass (sun or star) and stadiametric instrument will be required for this task. Accuracy of this device will be proportionate to the weight and complexity deemed justifiable for the mission. Both lens and lensless type instruments should be evaluated during the feasibility tests.

Sample Extraction. - The extraction of the specimen at a sample point will be accomplished with the use of the PLGT, or hand tool if the early feasibility tests prove that the latter technique is practical. Some of the methods which may be employed for extracting the sample are evaluated below with respect to value, damage hazard to space suit, and the time element:

1. Prying - Some flying chip hazard. Difficult operation with hand tools under 1/6 G.

2. Hammering - Extreme flying chip hazard if hand tool is used. Use of the PLGT will eliminate this hazard by containment of the flying chips within the debris shield.

3. Chiseling - Difficult with hand tool unless sample is retrieved from a ledge where the astronaut is not required to bend. The extreme danger of the hammer deflecting from the chisel and hitting the astronaut's hand limits the value of this technique. Chiseling can be accomplished with the PLGT by use of the appropriate attachment.

4. Coring - Slower time of extraction, but excellent record of lithology. Use of a hand tool (soil sampler) would limit coring to soft materials such as dust, pumice and tuff. A power tool capability will be required for coring in hard materials such as basalt and obsidian. It may not be possible to collect samples any other way from a rounded, non-jointed basalt or granite knob.

5. "Grab" Sampling - Loose materials such as dust and rock fragments may be collected in a minimum time with little or no hazard, but the samples may not be in place. A clamping or scoop device will probably be required for this operation. The best average solution for the astronaut will be to collect some "grab" samples if they appear to be the same material as that on which the loose material rests.

Sample Analysis. - Time and dexterity restrictions will limit specimen analysis to a cursory visual examination, perhaps aided by a simple magnifier. The chief problem will be the working distance limitation imposed by the spacesuit visor which will reduce the field of view obtainable with the magnifier. The analytical observations to be transmitted back to the recorder include:

1. Nature of the material

2. Color of material - Color stripes painted on the PLGT may assist the astronaut in correctly identifying rock colors under the harsh lighting conditions of the lunar surface.

3. Texture of the material - e.g. for a basalt - aphanitic, very fine-grained, etc.

4. Rock structure - vesicles, flow banding, etc.

5. Unconsolidated material or dust - consistency and depth should be determined if possible.

Sample Packaging.- The lunar surface specimens will be packaged and sealed in mylar-type bags immediately after their retrieval at the sampling locations. The bags will be pre-numbered so that the observations and descriptions regarding a particular sample can subsequently be compared with the detailed sample analysis after return to earth. A large sample container must be supplied for the roving astronaut for temporary storage of the numbered specimen bags until they are transported back to the LEM and packaged in the earth-return "rock boxes." This container should be integrated with the PLGT rather than strapped to the astronaut.

Samples obtained by coring will be approximately one inch in diameter and a maximum of four inches long. Standard geological rock samples procured for analytical purposes are usually cubes with dimensions of 4 x 3 x 1 inches. The restrictions of the space suit will not allow the lunar surface astronaut to accurately shape the specimens obtained by hammering or chipping. However, he should strive to obtain samples within the range of 2 x 2 x 1 to 4 x 3 x 1 inches to avoid additional time consuming trimming with the PLGT after the sample has been detached from the surface.

The PLGT sample container should possess sufficient volume to temporarily stow the specimens obtained during each traverse. A total of 12 samples will be procured as a representative suite for each traverse. Therefore, considering a maximum sample size of 4 x 3 x 1 (12 cubic inches) and a packing density (ratio of volume occupied by rock to total sample container volume) of 0.5, a volume of approximately 288 cubic inches will be required for the representative suite. In addition, space should be provided for special-interest samples (rock outcrops, small crater rims, etc.) and for the possibility that the traverse may encompass an area greater than the recommended 30-degree sector. A container capacity of 24 samples is recommended. Assuming a possible specific gravity range of 0.5 to 3.0, the 24 samples could weigh in the range of 5 to 30 earth pounds. At the completion of each traverse, the samples will be removed from the PLGT container and temporarily placed near the LEM until the final "rock box" packaging operation is accomplished.

Measurements.- If time permits, a number of structural measurements can be performed to supplement the information which subsequently will be extracted from the lunar surface photographs. These measurements may include dip and strike measurements, flow and compaction banding, joints, slope of surface, ridge trends, orientation of elongate vesicles, crater geometry and other similar tasks. Many of these measurements will require the use of a mechanical clinometer and a scale in addition to the previously discussed azimuth and stadia instrument.

Final Packaging and Weighing. - Upon completion of the exploratory traverses, the lunar surface samples will be assorted near the LEM for final packaging in the earth return "rock boxes." A total of 144 samples would be available if the recommended 24 samples were obtained on each of the six traverses. If the samples were of standard geological size (4 x 3 x 1 inch) and a packing density of 0.5 is assumed, then the 144 samples would completely fill the two cubic foot rock boxes.

The 144 samples may possibly exceed the return payload capability of the LEM. Therefore, the astronaut must weigh each of the rock boxes to insure that their combined weight does not exceed 80 ± 1 earth pounds. Additional specimens may be added or removed from the rock boxes in order to satisfy the weight and volume requirements.

POTENTIAL DESIGN APPROACHES

Powered Lunar Geologist Tool (PLGT)

General. - The initial design approaches outlined in the First Quarterly Report are currently being incorporated into the prototype model of the PLGT. A tentative design for the basic PLGT has been completed, and fabrication of the device is approximately 80 per cent complete. Several minor technical changes, and elaborations of design approaches are outlined below.

Design Criteria. - Initial feasibility tests have revealed that core diameters of at least one inch are required in order to prevent excessive core breakage. This design parameter applies for both rotary diamond, and rotary percussion coring. Therefore, the PLGT design is oriented around the larger diameter core rather than the five-eighths inch core, even though the latter size core would theoretically require less drilling power.

The PLGT will be designed for both rotary and rotary percussion drilling. The pure rotary drilling is required for the prevention of excessive core breakage in soft materials such as pumice and tuff, while the rotary percussion is required to obtain satisfactory penetration of harder materials such as basalt and obsidian.

Battery Selection. - The Electric Storage Battery Company could not supply the SS-25B silver zinc cell within the envelope dimensions originally specified. Since this necessitated re-design of the PLGT power pack housing, it was decided to utilize a similar unsealed silver zinc cell (HR-21) manufactured by the Yardney Electric Corporation for the prototype model. The fourteen HR-21 cells will be packaged in a sealed container capable of a 2 to 3 psi pressurization to prevent evaporation of the electrolyte. The design specifications for the HR-21 silver zinc cells are listed below.

Type:	HR-21 Yardney Silvercel Battery
Nominal Capacity	20 Amps-Hours
Nominal Voltage:	1.5 Volts
Energy Density:	45 watt-hours/lb (@ 75°F, 20 amps, exclusive of outer case) 3.2 watt-hours/in^3 (@ 75°F, 20 amps, exclusive of outer case)
Cycle Life:	30
Physical Characteristics:	
Weight:	15.5 oz/cell
Size:	7-17/32 x 2-19/64 x 0.8 inches

There are several development projects currently in progress for improving the efficiency of silver-zinc cells. It is anticipated that the power pack selected for the final model space-qualified PLGT's will exhibit significant improvements, with regards to packaging and power-to-weight ratios. The program objectives for the prototype PLGT will be achieved with the HR-21 cell, and additional program expenditures for developmental batteries is not warranted at this time.

Motor Design.- Fabrication of the electric motor for the PLGT has been completed. The motor was brake tested to determine its operating efficiency over the entire power input range. The peak motor efficiency occurred at the nominal operating load current of 25 amperes. Figure 2 illustrates the operating parameters of the motor.

Mechanism.- The percussive action required for the PLGT is obtained by a hammering mechanism using a rise cam and drive spring arrangement. A variable pressure spring is incorporated which can be operated by the astronaut to control impact energy.

The PLGT will also incorporate a slip clutch to limit reactive torque to approximately 12 foot-pounds. Previous tests performed in the Martin Lunar Gravity Simulator revealed that the upper limit of reactive torque restraint by the astronaut is approximately 13-16 foot-pounds.

The completed lower portion of the PLGT (Gear Housing and Motor Cover) is shown in Figure 3.

PLGT Envelope.- A "boiler-plate" mockup of the PLGT which was used to evaluate possible interface problems with the spacesuited astronaut is shown in Figure 4. The mockup is approximately full size, although the accessory equipment (compass, clinometers, sample carrying device, tripod) should not be considered representative of the operating PLGT.

The results of the spacesuit interface evaluation with the PLGT is presented in the feasibility testing section of this report.

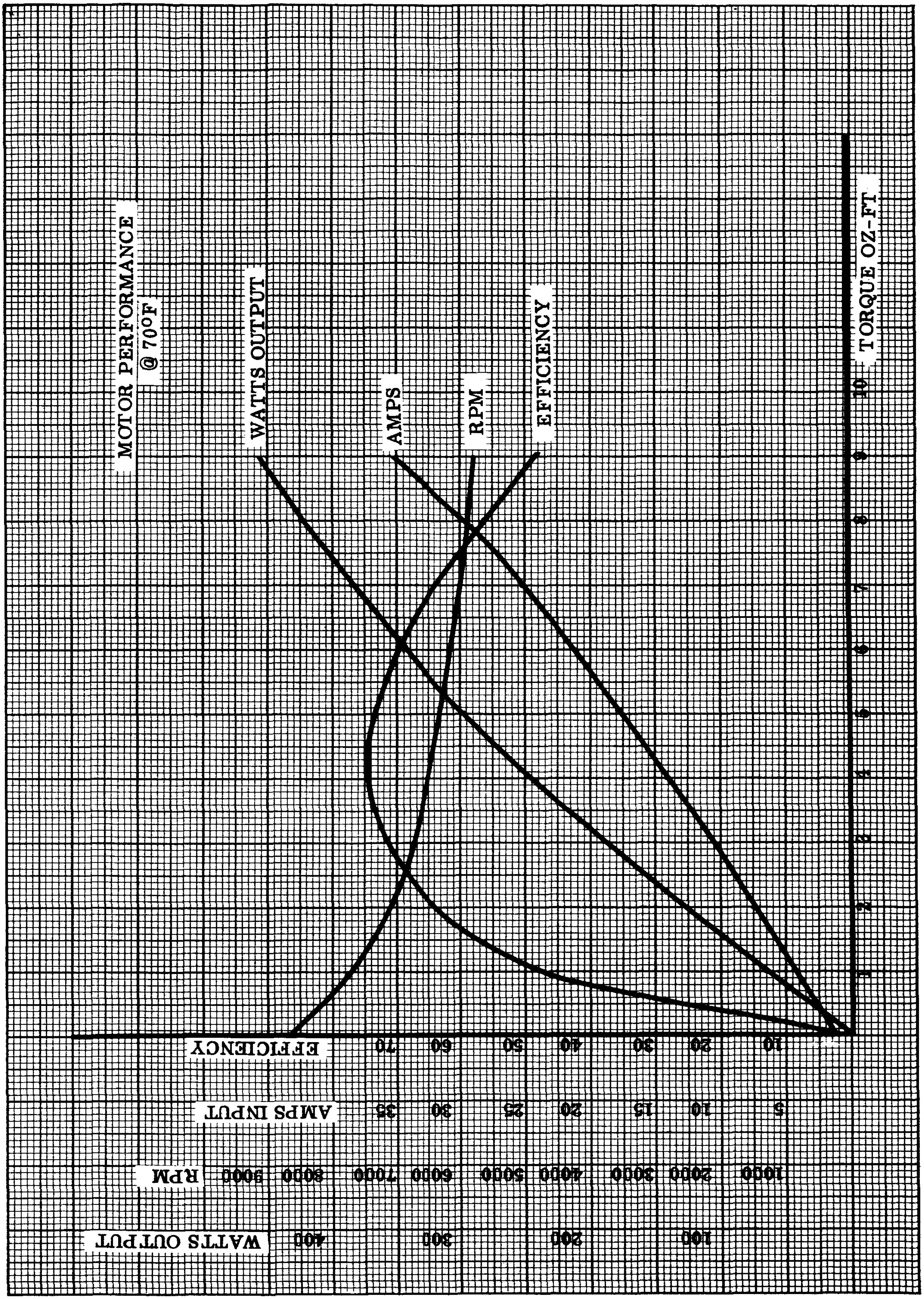

Figure 2. Motor Performance

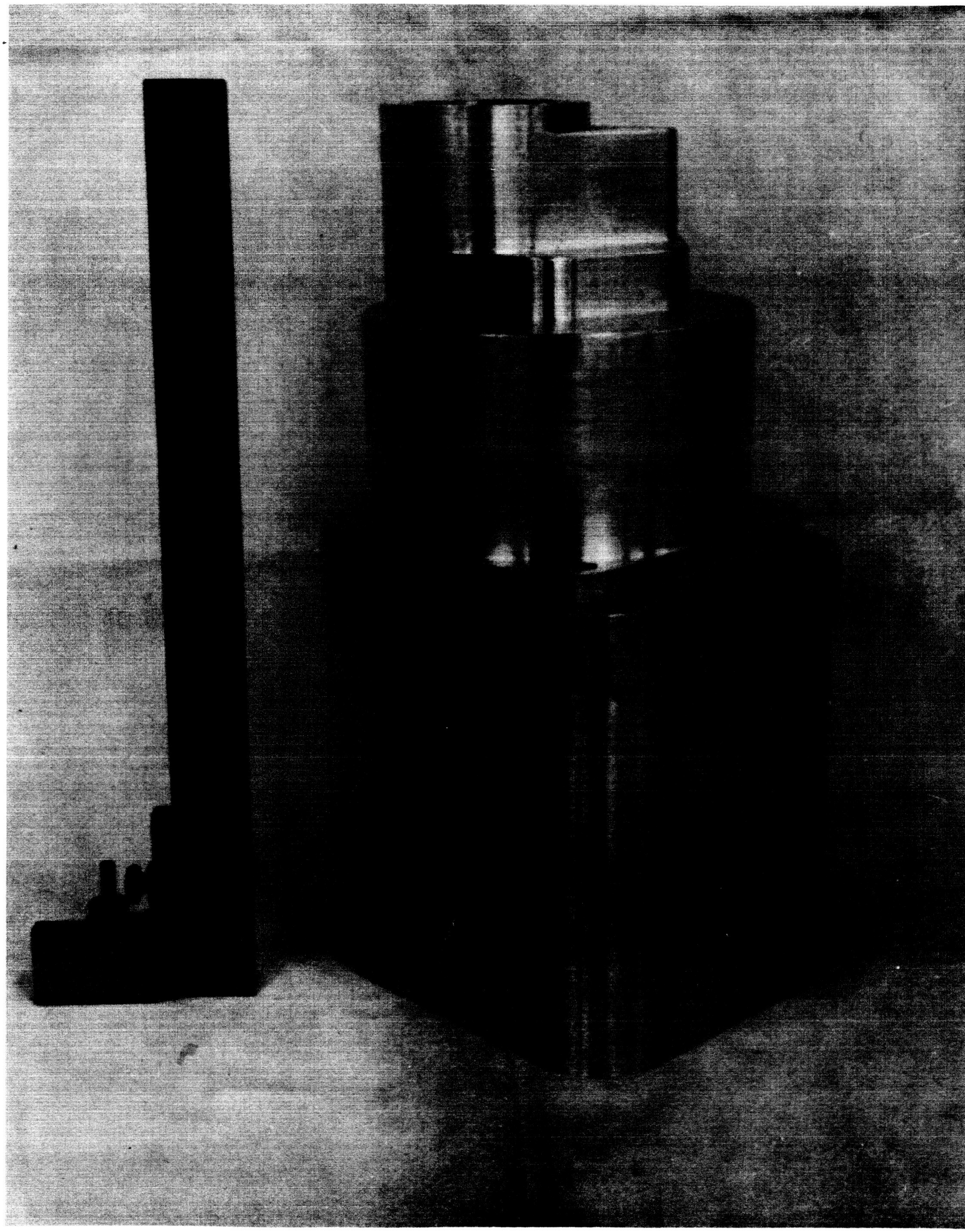

Figure 3. PLGT Gear Housing and Motor Cover

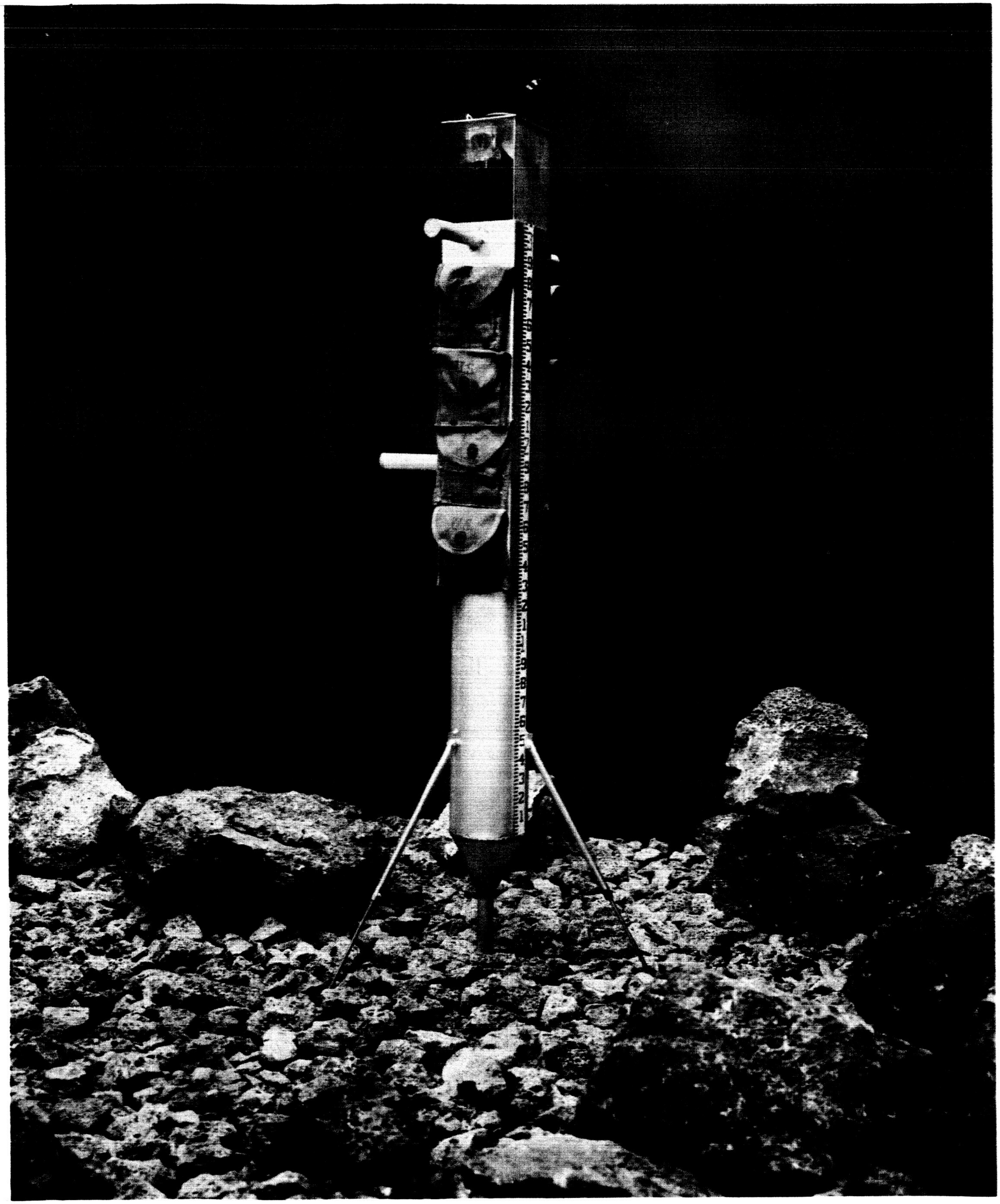

Figure 4. PLGT Mockup

Lunar Geological Mapping Instrument (STAPEL)

General. - Terrestrial surface geological mapping is often accomplished by use of a transit or survey alidade along with a variety of accompanying equipment such as maps, stadia rod, plumb bob and measuring tape. However, the majority of field geological mapping is accomplished by use of a simple magnetic compass such as the Brunton "pocket transit." This device is preferred by field geologists because it is lightweight, can be operated by one man, and possesses sufficient accuracy (1-2 degrees) for the performance of most geological mapping tasks. The Brunton is a multipurpose instrument which can be used for leveling, strike and dip measurement of rock strata, magnetic bearing and elevation of topographic features, and many other related tasks. Although the Brunton compass does not possess a stadia measurement capability, "pace traverses" are often employed to obtain distance measurements when a high degree of accuracy is not required.

A device similar to the Brunton compass would be desirable for use by the lunar astronauts during the early LEM exploratory landings. Optical interface problems and weight penalties may not warrant the use of the more elaborate instruments such as the transit and survey alidade. In addition, the geological mapping accuracy requirement within the limited walking range of the lunar surface astronaut can be attained by use of a special purpose lensless instrument which is described in the following paragraphs. Obviously, the Brunton compass could not be utilized on the lunar surface because of the absence of an appreciable magnetic field, and the boiling and freezing problems which may be encountered with the liquid leveling device.

Lensless Stadiametric Pelorus. - A simple navigational device can be incorporated as an integral part of the PLGT to enable the astronaut to locate his position relative to the known selenographic coordinates of the LEM. This relative location would consist of a bearing angle and horizontal distance from the astronaut to the LEM. The instrument can be positioned on the end of the PLGT so that when the latter is oriented vertically for normal use, it provides a convenient stand for the navigation device.

The simplest navigational instrument configuration would consist of a stadiametric pelorus (STAPEL). The pelorus consists of an arm pivoted about its center on a compass card. Two vertical sighting posts are mounted on this arm, one on each end. Alignment of the sighting posts (and arm) with a distant object permits a relative bearing to be measured. The stadiometer measures the vertical subtended angle of an object of known size and, therefore, permits a determination of range to the object. The STAPEL would require a gravity-sensing device for leveling of the compass card. A sketch of the proposed instrument is illustrated in Figure 5.

Stadiametric Distance Determination. - The stadiametric geometry for the STAPEL is illustrated in Figure 6. Range determination is accomplished by the solution of similar right triangles. The parameters of the stadia alignment

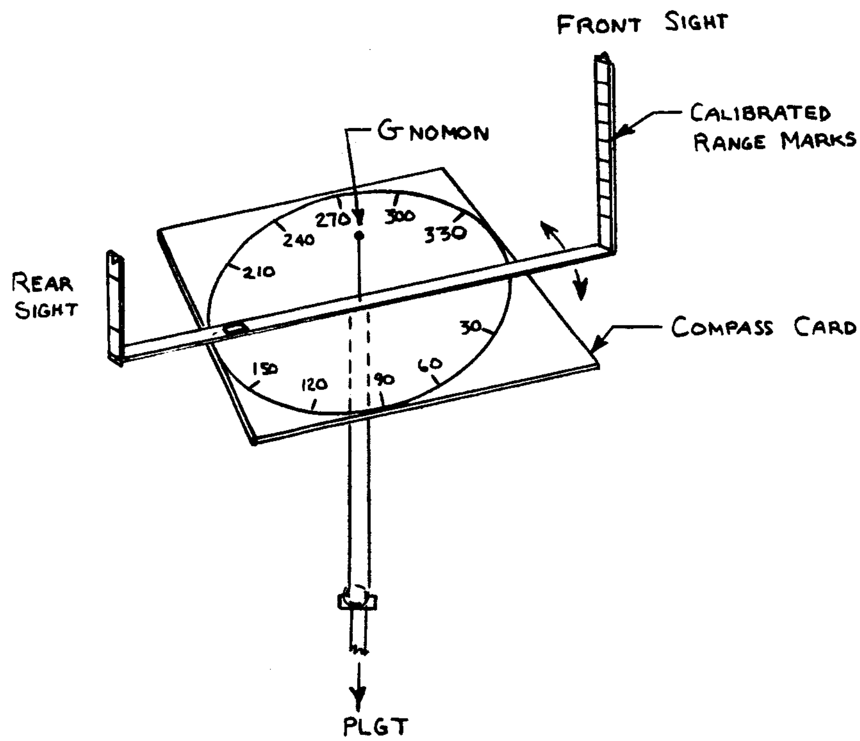

Figure 5. Lensless Stadiametric Pelorus (STAPEL)

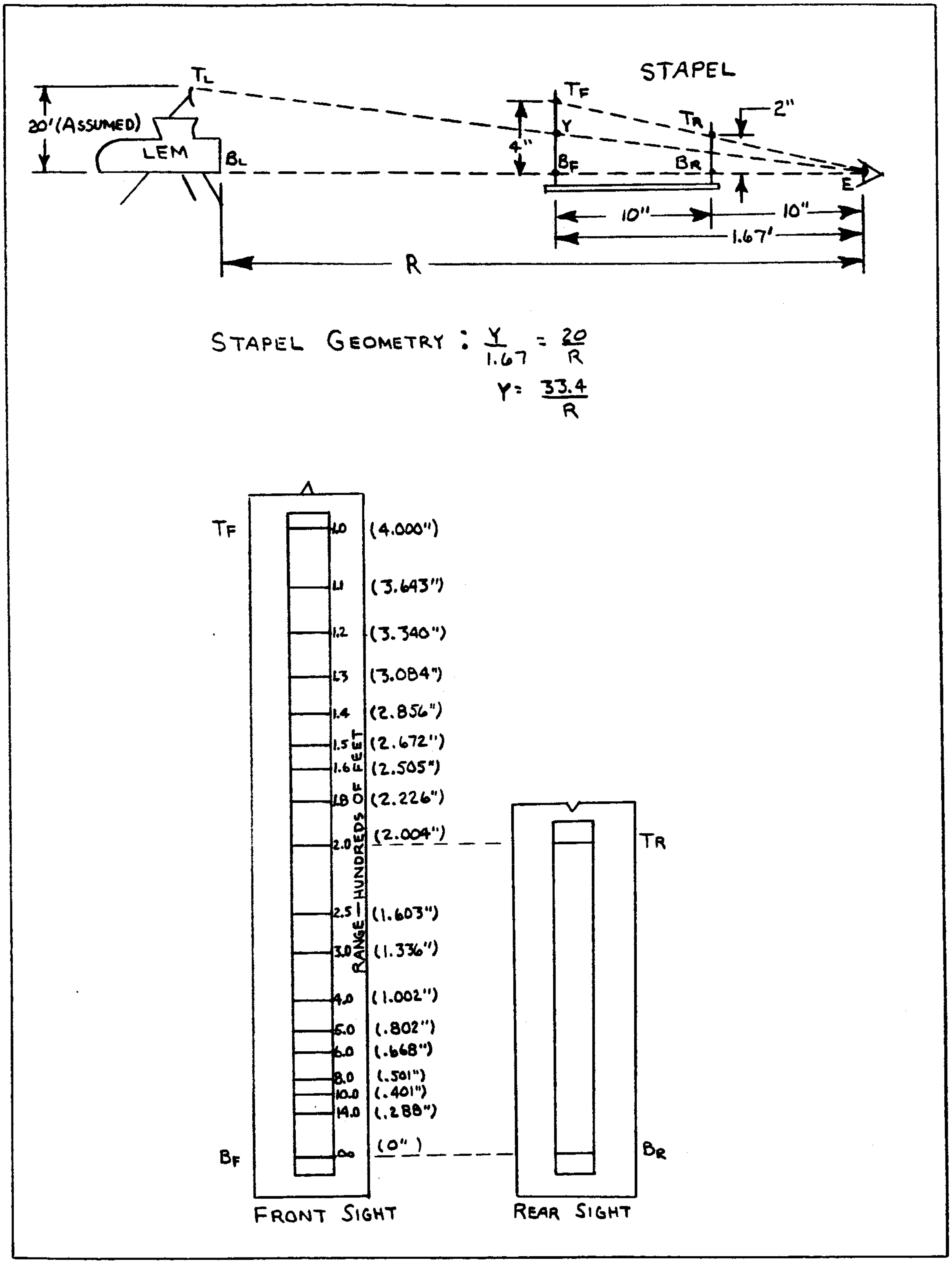

Figure 6. Stadiametric Geometry

posts establish the reference triangle, thus permitting the similar triangle incorporating the known height of the LEM vehicle to be optically solved for "ranges" as described below.

The arm of the STAPEL is rotated until the front and rear posts are aligned with the LEM. The astronaut then adjusts his eye (E) to align the bottom marks (B_f and B_r) on the front and rear sights as shown in Figure 6. This establishes a zero reference line which must be adjusted to coincide with the bottom reference (B_l) on the LEM. The latter adjustment can be accomplished by pivoting the entire instrument toward or away from the LEM. Of course, the astronaut must move his eye as he performs this adjustment to maintain colinearity of B_f, B_r, and E while aligning with B_l. The instrument is then left in this position and the astronaut must move his eye (head) along the line B_l, B_f, B_r, E until the top marks Tf and T_r on the vertical alignment sights are also superimposed. This movement will position the astronaut's eye at the correct distance from the scale on the forward sight. The scale can be calibrated for this eye position and known height of the LEM such that the top reference T_l of the LEM will coincide with the correct range displacement from the vehicle.

The following parameters will be assumed for the prototype STAPEL:

Front Sight Height B_fT_f = 4 inches

Rear Sight Height B_rT_r = 2 inches

Arm Length B_fB_r = 10 inches

Eye to Front Post B_fE = 20 inches

LEM Reference T_lB_l - 20 feet

A calibrated stadia scale can be constructed (see Figure 6) by solution of the similar triangles using the assumed parameters. Clearly, such a stadiametric measurement will not be very accurate as the 1000-foot displacement is approached. Modification of the instrument geometry or dimensions will not significantly improve the accuracy. The basic problem is caused by the fact that the 20-foot reference height assumed for the LEM vehicle subtends the relatively small angle of 1.15 degrees at 1000 feet.

The assumed geometry of the prototype STAPEL will not permit stadia measurements to be obtained at a range closer than 100 feet using the 20-foot reference marks of the LEM vehicle. This is caused by the fact that the maximum scale height B_fT_f (4 inches) will subtend the entire 20-foot reference on the LEM at a range of 100 feet. However, the problem of measuring distances less than 100 feet can be overcome by "marking" the LEM with another reference mark equal to 1/10th of the distance from the bottom to the top references. For the assumed case of 20 feet for T_lB_l, the second reference could be established by painting a small line around the LEM at a distance of two feet above

B_1. The scale calibrations on the STAPEL would then be interpreted as tens of feet (instead of hundreds), and the device would be capable of measuring distances down to ten feet.

Stadiametric Accuracy. - The unaided human eye can generally resolve an angle as small as one minute of arc. Assume, therefore, that an error of this magnitude occurs in the sighting of each of the six objects which must be observed in one stadiametric measurement as previously described. If these individual errors are all added, the total angular error would be 0.1 degrees (0.002 rad.). The effect of this angular uncertainty on the range can be determined by differentiating the expression $h = r \tan \Theta$ for the stadiametric range. Here, h is the known reference height, r is the range from the astronaut to the LEM, and Θ is the measured angle. The differential gives:

$$O = \tan \Theta \, dr + r \sec^2 \Theta \, d \Theta$$

$$\text{or} \quad dr = \frac{-r \sec^2 \Theta \, d \Theta}{\tan \Theta}$$

$$= \frac{-r \, (1 + \tan^2 \Theta) \, d \Theta}{\tan \Theta}$$

$$\frac{dr}{r} = - \left(\frac{r}{h} + \frac{h}{r}\right) d \Theta$$

For an angular error $d\Theta = .002$ radians, a value of h/r max = 0.02 (h = 20 feet @ r = 1000 or h = 2 feet @ r = 100). This expression results in the curve shown in Figure 7. Thus, for the 20 foot height, the abscissa ranges from 100 to 1000 feet, and the corresponding ordinate errors are 1 to 100 feet respectively. Similarly, for the abscissa ranging from 10 to 100 feet, the corresponding ordinate errors are 0.1 to 10 feet.

Pelorus Determination of Bearing Angle. - In order to relate the bearing angles to the lunar coordinate system, it is necessary to level the instrument with the local horizon. This can be accomplished by means of the mechanical inclinometers which will be integrated with the STAPEL. It will be assumed that the location (latitude and longitude) of the LEM is known on the surface of the moon.

Since the compass card will be arbitrarily oriented, a known reference can be established by reading the bearing angle β_s after alignment of the front and rear posts with a known star (or the sun). A reference angle can also be established by noting the position of the sun's shadow as cast by the gnomon. After noting the angle β_s, the pivot arm of the STAPEL can be rotated about the stationary compass card and aligned with the LEM vehicle where the second angle β_l is measured.

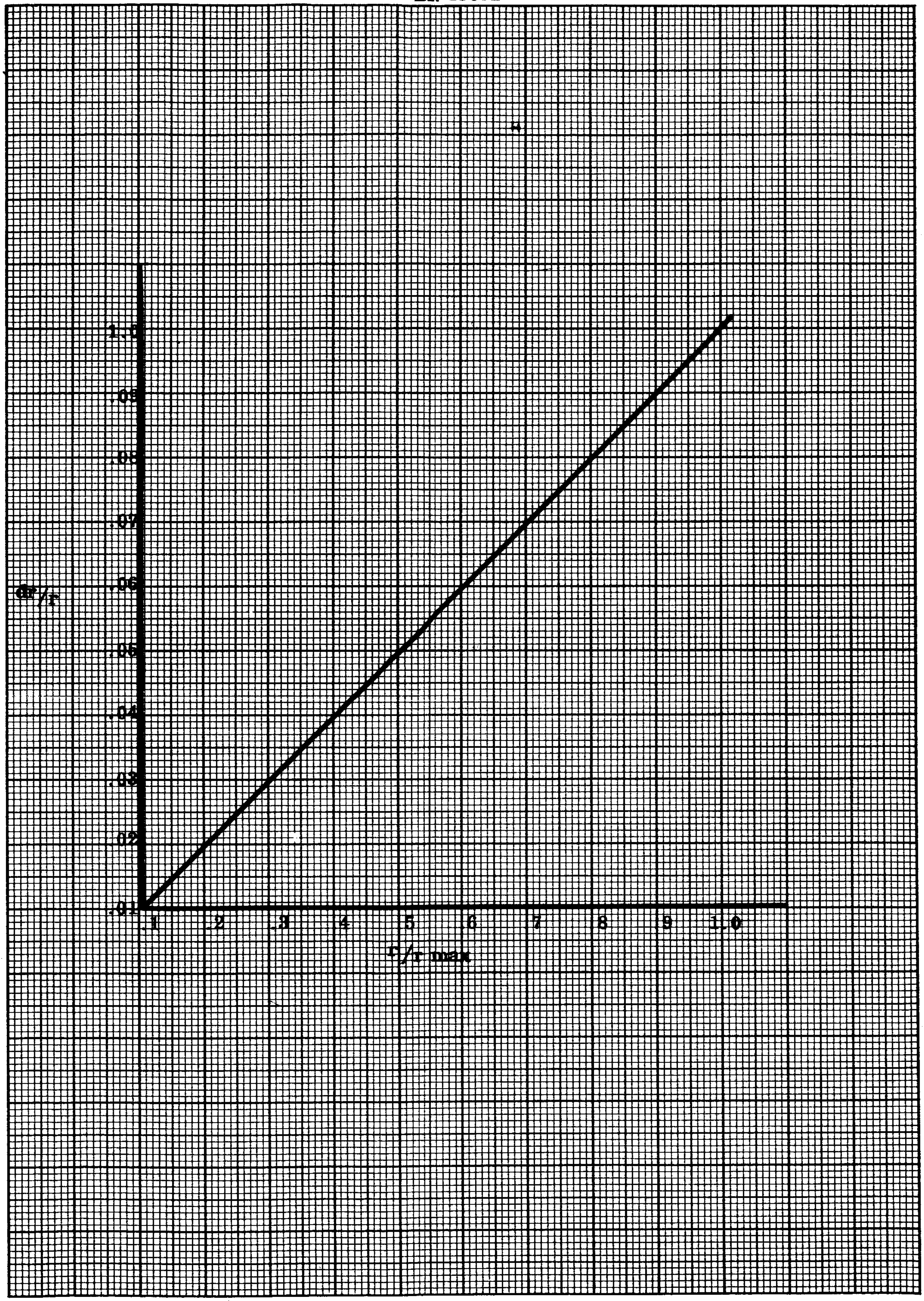

Figure 7. Stadiametric Range Uncertainty

Both the stadiametric and bearing angle measurements obtained by the lunar surface astronaut should be recorded on a "time based" tape recorder. The location of the astronaut relative to the LEM can later be determined from the STAPEL measurements and known bearing of the sighted star (or sun) for the particular lunar latitude, longitude, and time. The technique for calculating the true relative bearing angle β in the lunar reference system is described in Appendix A.

Improved Accuracy of STAPLE. - A precision machined and aligned STAPEL would probably permit pelorus angles to be measured within $\pm 0.1^{o}$ accuracy. Thus, the computed bearing angle (involving two pelorus angle measurements) would be accurate within $\pm 0.2^{o}$. Therefore, at a range of 1000 feet, a cross-range position accuracy of $\pm$ 5 feet could be obtained. The largest error, as previously computed, can be expected in the stadiametric measurement at 1000 feet, and could be on the order of 100 feet.

This error could be reduced if the geological sampling procedure starts from the LEM and proceeds outward. As the distance from the LEM reaches just beyond 100 feet (where the range is accurate to 1 foot) a series of four sample locations equally spaced around the LEM can be marked with colored posts so as to be plainly visible from distances outward to 1000 feet. Although the true lunar positions of the marker posts will not be immediately known to the astronaut, the STAPEL measurements for these posts can be later reduced to true bearing angles using the computation described in Appendix A.

Thus, for surveys extending outward from the accurately positioned marker posts, the position of the astronaut can be obtained by triangulation. Bearings can be measured with the STAPEL relative to any pair of the marker posts and the LEM. Use of these marker posts located approximately 100 feet from the LEM will reduce the range uncertainty at 1000 feet from 100 to 20 feet. Further reduction is possible if additional reference locations are established at greater distances from the LEM.

Sample Weighing Device

General. A weighing device must be included in the lunar geological tool kit to enable the LEM astronaut to weigh the earth-return sample boxes. It is anticipated that the geological specimens collected from the lunar surface will be packaged in two containers with each measuring one cubic foot in volume and weighing in the range of 25 to 65 earth pounds. The combined weight of the earth-return payload must not exceed 80 pounds, and the weighing accuracy must be within plus-or-minus one pound. The latter specification is required in order to obtain center-of-gravity information for the LEM Ascent Stage and Command Module.

Commercial Spring and Balance Scales. The simplicity of a direct-reading spring scale would be extremely desirable for use by the spacesuited astronaut. However, a survey of available spring devices revealed that the required tolerance would be difficult to attain over the wide lunar temperature range. Although the early LEM landings will probably occur during the lunar day, the possibility that the weighing procedure could occur in the LEM shadow as well as in the direct sunlight complicates the incorporation of a dependable temperature compensation for a spring device.

Utilization of a balance-type scale reduces the temperature and accuracy problems inherent with the spring scale. However, the balance scales are usually somewhat heavier than their counterparts in spring devices and the measurement procedure is more difficult and time consuming for the astronaut. A survey of commercial balance scales revealed that the lightest available device suitable for the lunar surface application weighed approximately ten pounds. Although the weight of this particular device could probably be reduced to six pounds by removal or modification of supporting structures, the excessive weight is still considered intolerable.

PLGT Integrated Scale. The possible usage of the PLGT telescoping section as a balance arm for the weighing device in addition to its primary function of supporting the compass platform would result in an overall weight savings. Counter-balancing mass for the scale could be provided by a pre-weighed component of the LEM or geological tool kit in lieu of transporting calibrated weights to the lunar surface as part of the LEM payload. A simple design approach for the weighing device is presented below.

The overall length of the PLGT is expected to be approximately 40 inches, and the telescoping support arm for the compass platform should be a minimum of 20 inches. Therefore, the balance arm of the weighing device will be initially designed to this specification. The PLGT battery, which is expected to weigh a minimum of 16 pounds, can be used as a counterweight. Since the weight of each battery pack may vary somewhat from the anticipated nominal, preflight weighing of each pack would be required. Several positioning marks would be scribed on the balance arm (see figure 8) to compensate for variations in individual battery pack counter-balancing weight.

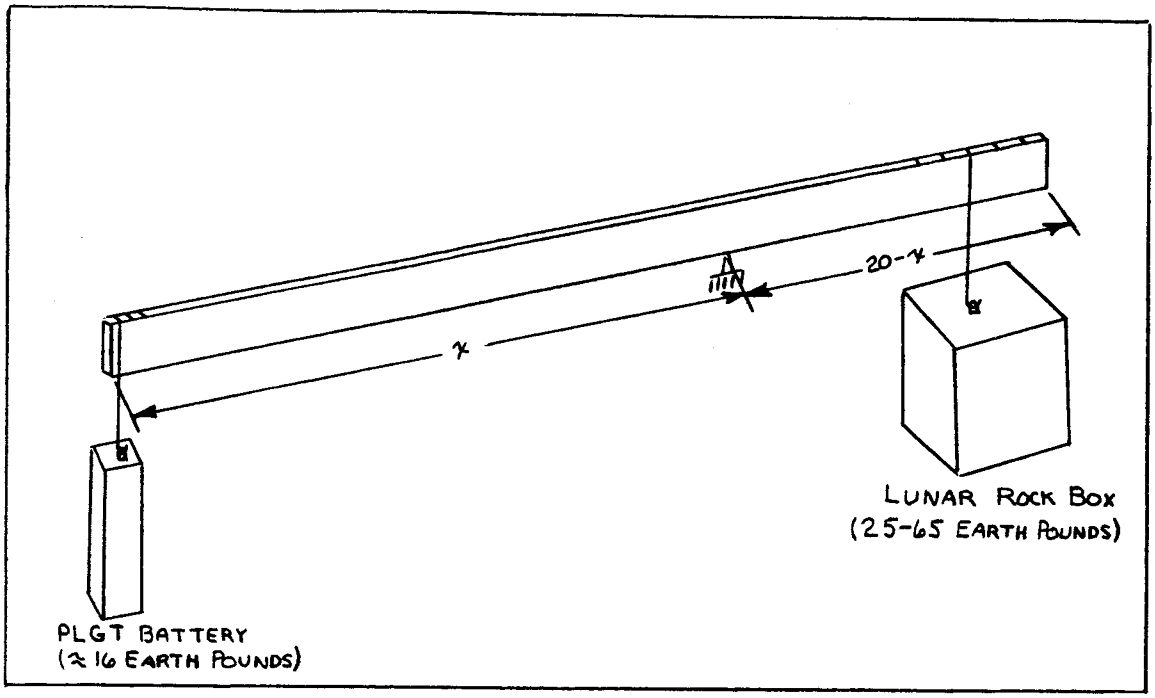

Figure 8. Beam Scale

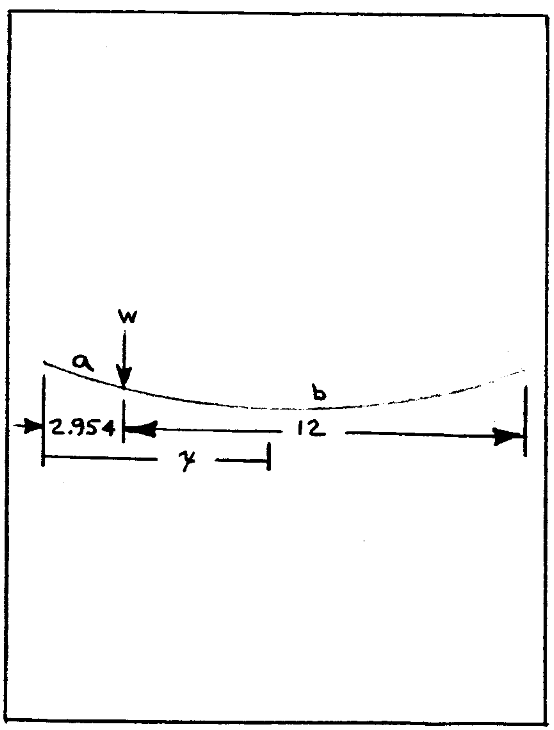

Figure 9. Deflection at Fulcrum

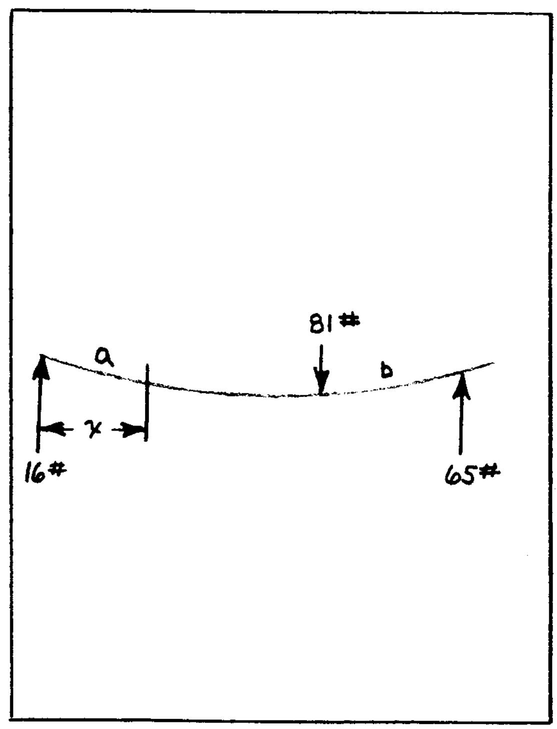

Figure 10. Point of Maximum Deflection

The beam should be designed so that the 16-pound minimum battery pack weight would be positioned at the extreme left edge. Additional notches can be provided (closer to knife edge) for heavier battery packs. The position of the knife edge for maximum usage of the balance beam is given by:

$$16\,x = 25\,(20-x) \qquad x = 12.195 \text{ inches}$$

For simplicity, consider:

$$x = 12.000 \text{ inches} \quad \text{and} \quad m = 16 \times 12 = 192 \text{ inch-pounds}$$

Therefore, the scale calibration for the "rock box" side of the knife edge should be designed to balance 192 inch-pounds. For each scale calibration mark denoting pound-increments from 25 to 65 pounds, the distance d from the knife edge is given by:

$$d = \frac{192}{w} \text{ (inch-pounds)} \qquad w = \text{weight of rock box}$$

For feasibility test purposes, calibration scribes should be machined on the low, middle, and high range areas of the test beam. These calculations and incremental differences between adjacent scribe marks are tabulated in Table 1.

The material selected for the weighing device beam consists of 7075-T6 aluminum alloy which can be treated by the Martin hardcoat process. This process will reduce sliding friction in the lunar vacuum. In order to insure that excessive bending will not occur with the selected 0.125 x 1 x 20 inch beam, the following analysis is presented.

The moment of inertia of the beam is given by:

$$I = \frac{0.125 \times 1^3}{12} = 0.010417$$

$$M = 192 \text{ inch-pounds (max.)}$$

$$F_b = \frac{mc}{I} = \frac{192 \times 0.5}{0.010417} = 9210 \text{ psi (fiber stress)}$$

$$F_s = \frac{S}{A} = \frac{65}{0.125} = 520 \text{ psi (shear stress)}$$

Stress ratio at 300°F. is given by:

$$R_1 = \frac{9210}{70000 \times 0.7} = 0.188$$

$$R_2 = \frac{520}{43000 \times 0.6} = 0.0202$$

$$M_s = \frac{1}{R_1 + R_2} - 1 = 380\% \text{ (safety margin)}$$

The beam deflection at the knife edge is given by:

$$y = \frac{Wa\ (1 - x)}{6\ E\ I\ 1}\left[2\ 1\ b - b^2 - (1 - x)^2\right] \quad Wa = M = 192$$

$$y = \frac{192 \times 2.954\ [29.908 \times 12 - 144 - 144]}{6 \times 10.3 \times 10^6 \times .010417 \times 14.954}$$

$$= 0.00416 \text{ inch (ref. figure 9)}$$

The maximum beam deflection is given by:

$$\max y \text{ at } x = \sqrt{1/3\ a\ (a + 2b)} \quad \text{when } a > b$$

$$x = \sqrt{\frac{12 \times 17.908}{3}} = 8.475$$

$$\therefore \max y = \frac{W\ a\ b}{27\ E\ I\ 1}\ (a + 2b)\ \left[3a\ (a + 2b)\right]^{1/2}$$

$$= \frac{192 \times 2.954 \times 17.908\ (36 \times 17.908)^{1/2}}{27 \times 10.3 \times 10^6 \times .014017 \times 14.954}$$

$$= 0.00445 \text{ inches (ref. figure 10)}$$

In summary, the beam deflections are considered to be negligible with a maximum of 65 pounds weight. The bending of the beam will be reduced even further during operation in the lunar environment since the earth weight of the rock boxes will be reduced by a factor of one-sixth.

Thermal expansion (or contraction) of the scale beam due to temperature changes will obviously not affect weighing accuracy of the device. The thermal expansion for aluminum is given by:

$$1 = 1\,o\ (1 + \alpha\ \Delta t)$$

where 1 = length of the beam due to temperature variation

$1\,o$ = length of the beam at room temperature

α = coefficient of thermal expansion

Δt = temperature change

$$1 = 20\ \left[1 + 1.28 \times 10^{-5}\ (200)\right] \text{ (considering beam at } 270^{\circ}\text{F.)}$$

$$= 20.0512 \text{ inches}$$

This change in length would theoretically occur equally over the entire span of the balance beam thus maintaining an equilibrium condition at any temperature.

Rock Box Weight	Distance From Fulcrum To Scale Scribes	Incremental Difference Between Scribes
25 Pounds	7.680 Inches	
26	7.385	0.295 Inches
27	7.111	0.274
28	6.857	0.254
29	6.621	0.236
30	6.400	0.221
45	4.267	
46	4.174	0.093
47	4.085	0.089
48	4.000	0.085
49	3.918	0.082
50	3.840	0.078
60	3.200	
61	3.148	0.052
62	3.097	0.051
63	3.048	0.049
64	3.000	0.048
65	2.954	0.046

Table 1. Calibration of Feasibility Sample Weighing Device

Geological Hand Lens

General. Use of the standard geologist's hand lens for examining lunar rock specimens will present some optical limitations for the spacesuited astronaut in addition to the usual dexterity problems. The primary optical limitation results from the helmet visor restricting the astronaut from bringing any object closer than approximately 2.5 inches from his eyes. It is apparent that this restriction must be examined in detail in order to evaluate the design requirements for a suitable lens.

Optical Considerations. The apparent size of an object is determined by the size of its retinal image, which in turn, depends upon the angle subtended by the object at the unaided eye. When one wishes to examine a small object in detail, it is brought closer to the eye in order that the angle subtended and the retinal image may be as large as possible. Since the eye cannot focus sharply on objects closer than the "near point" (generally accepted as 25 centimeters) a given object subtends the maximum possible angle at an unaided eye when placed at this point.

If a converging lens is placed between the eye and the object, the accommodation may in effect be increased. The object may then be brought closer to the eye than the "near point", and it will subtend a correspondingly larger angle. The magnifier forms a virtual image of the object and the eye "looks at" this virtual image. Since a normal eye can focus sharply on an object between the near point and infinity, the image can be seen equally clear if formed anywhere within this range.

Figure 11 illustrates the formation of a retinal image with the object located at the near point, where an angle of Θ is subtended at the eye. Figure 12 illustrates the use of a magnifier to form an image at infinity, with a subtended angle of Θ'. The angular magnification M is defined as the ratio of the angle Θ' to the angle Θ. It can be seen that the Θ ratio can be algebraically reduced to:

$$M = \frac{25}{f} \quad \text{where f is the lens focal length in centimeters}$$

In order to obtain maximum results when inspecting rock specimens, the magnifier should be held as close to the eye as possible while the sample is brought into focus on the far side of the lens. The rock sample will be in focus when it is moved into a position in back of the lens approximately equal to the focal length of the lens. Figure 13 illustrates the effects resulting from increasing the lens-to-eye distance. If the separation distance is substantially increased, the eye receives edge rays from the lens which are inherently the worst performers in any optical system. However, for a separation distance of 2.5 inches it is expected that the worst condition which will be encountered is a reduction in the field of view. This will be verified during the spacesuit feasibility tests before a final lens selection is made.

Lens Selection. If the hand-held magnifier proves to be feasible it is anticipated that two or three achromatic (triplet type) lenses will be selected in the 5 to 12 power range. The multiple lens arrangements are superior to the single lens magnifiers with respect to resolution and correction of chromatic and other aberrations. The magnifiers should be mounted on a single handle to facilitate storage and proper interfacing with the spacesuit gloves.

PLGT Surveying Platform

General. The geological task analysis requirement for range, bearing and angle-to-local vertical measuring instruments suggests the use of a surveying platform integrated with the basic PLGT. The surveying platform should be capable of leveling in "pitch" and "roll" independently of the vertical position of the PLGT with tripod extended. Two clinometers should be employed to facilitate pitch and roll leveling, or angular measurements to the local vertical. The surveying instrument (alidade or STAPEL) can be mounted on the platform when range and azimuth measurements are required at the various sampling locations on the lunar surface. A compass card should be employed to facilitate angular measurements within the local horizontal plane.

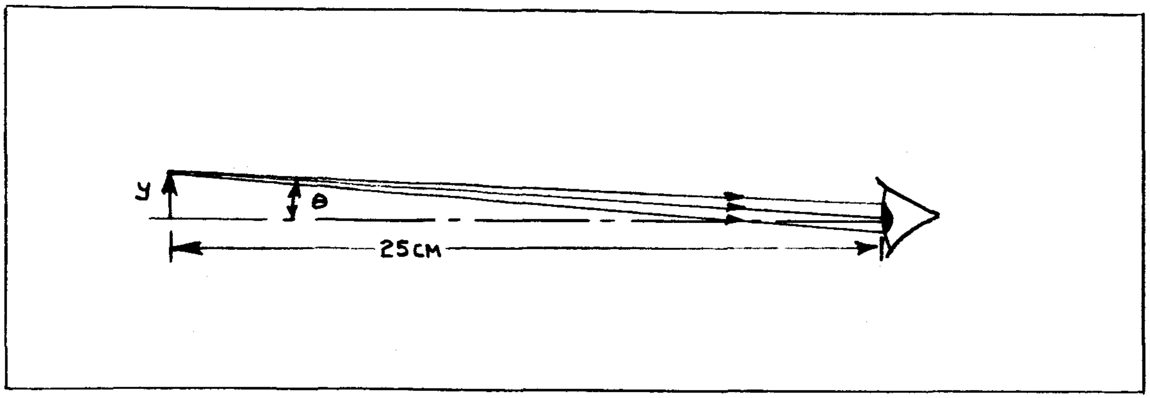

Figure 11. Unaided Eye With Object at Near Point

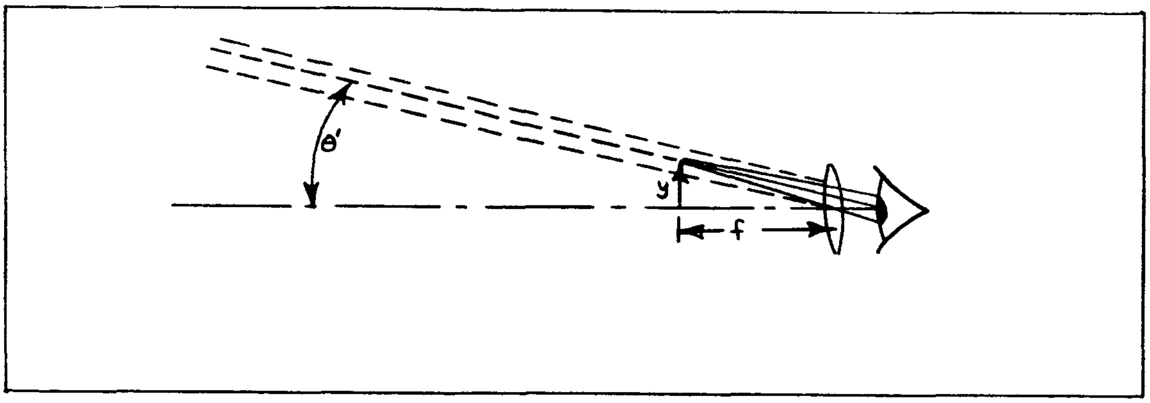

Figure 12. Formation of Image at Infinity With Magnifier

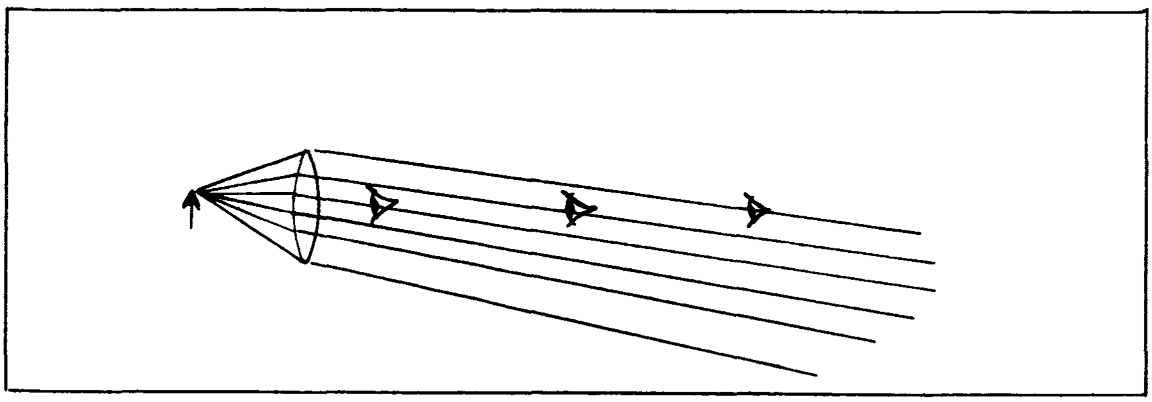

Figure 13. Effect of Lens-To-Eye Distance

Platform Design. Figure 14 illustrates the selected design approach for the surveying platform. The clinometers are designed and located "flush" with the surveying platform so that they can be easily read by the astronaut from his normal standing position. A compass card is inscribed on the platform for horizontal angular measurements with the STAPEL or alidade. The scales for both the clinometers and compass card will be inscribed so that they face the astronaut and thus eliminate unnecessary head and body movements. Pitch and roll leveling or angular adjustments are accomplished by two independent control levers.

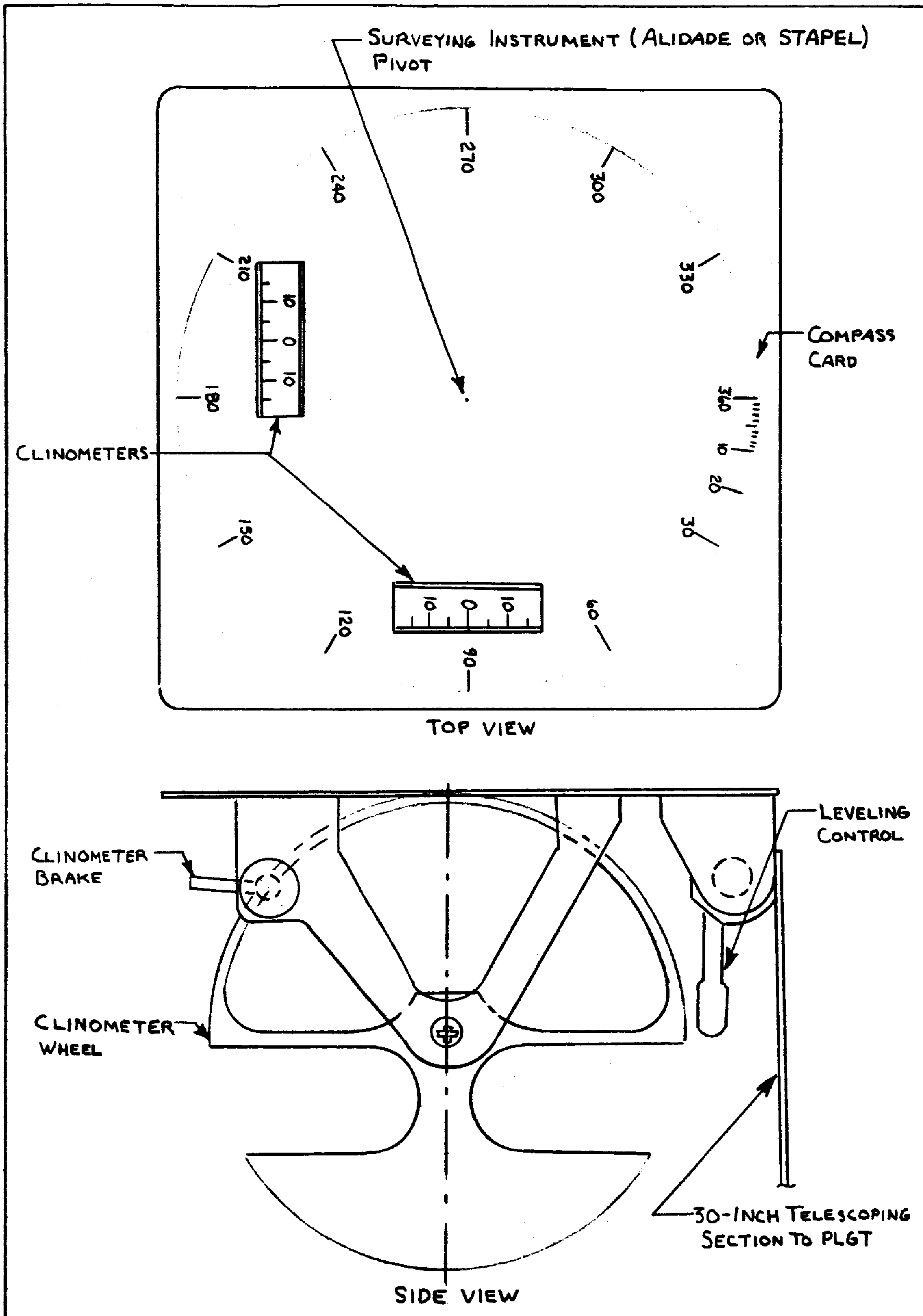

Figure 14. PLGT Surveying Platform

FEASIBILITY TESTS

General

A series of feasibility tests were conducted to evaluate the selected design approaches for the PLGT and auxiliary geological exploration tools. The majority of the tests were conducted by spacesuited subjects which permitted investigation of interface problems between the various tools and the spacesuit. The interface tests included evaluation of the following tools:

- PLGT Mockup (including sample carrying device, compass and clinometer)
- Geological Hand Tools (pick, hammer, chisel)
- Sample Weighing Device
- Hand Lens (magnifier)
- Standard Rotary Percussion Drill
- Sample Retriever
- Optical Transit
- STAPEL

PLGT Mockup

The PLGT mockup is illustrated in Figures 4 and 15. It consists basically of a full-scale metal envelope of the PLGT with commercial accessory attachments to simulate the sample carrying device, compass, and clinometers. The non-operating device weighs approximately five earth pounds which closely simulates the anticipated lunar weight of the PLGT.

Simulated coring and chipping operations with the PLGT presented no particular difficulties to the spacesuited subject. The overall dimensions of the PLGT - length, handle location and size as determined during early lunar gravity simulator tests - seemed adequate to the subject. There was some difficulty experienced by the subject in placing his left hand on the lower auxiliary handle while the right hand was grasping the upper-rear T-bar handle in the rock chipping position. The difficulty is caused by the glove restraint preventing the hand from pivoting in a left-right direction about the wrist joint. If this restraint is also inherent in the future Apollo suits, the PLGT auxiliary handle may require relocation at a 45-degree angle (pointing away from the astronaut in the chipping mode) in lieu of its present 90-degree position from the plane of the T-bar handles.

Raising and lowering of the PLGT telescoping support for the surveying platform presented no particular problems for the subject. However, considerable head and body movements were required in order to obtain readings from the side scale clinometers and compass. It was obvious that the final design for the surveying platform should include instruments which can be

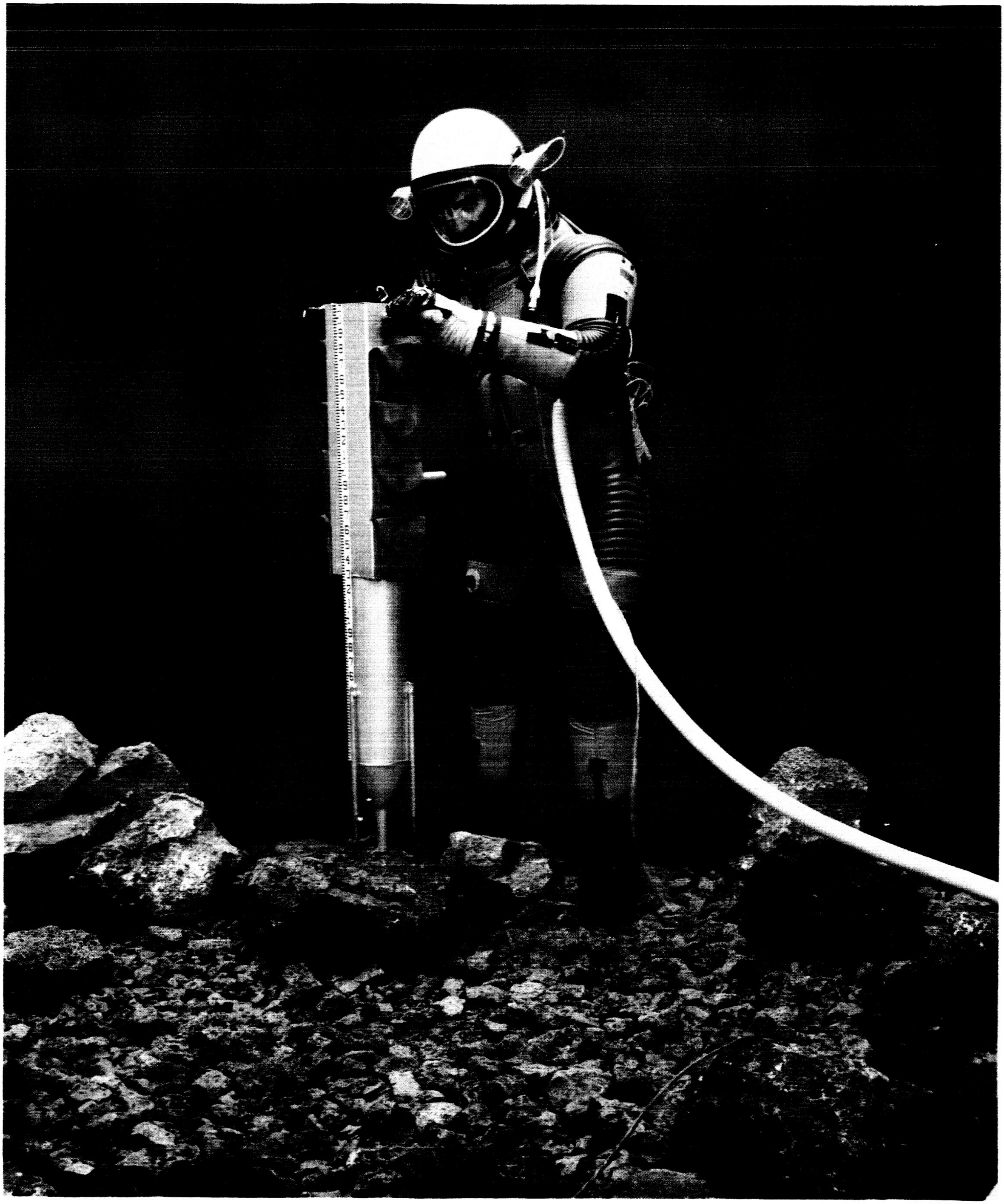

Figure 15. PLGT - Spacesuit Interface Test

read from the topside by the astronaut. The scale numerals should be inscribed with a common orientation so that they all can be easily read from one standing position.

The sample container devices used for the feasibility tests were small surplus packets which employed snap-type fasteners for securing the flaps. The spacesuited subjects encountered no particular problems while depositing or removing rock samples from the packets. The final model sample carrying device will, of course, require considerably more stowage volume than was available with the test packets.

Geological Sampling Hand Tools

Several tests were conducted to evaluate the capability of a spacesuited subject to hammer and chisel specimens from rock outcrops using standard geological hand tools. Some of these tools are illustrated in Figure 16.

It was determined that specimens can be hammered or chipped from moderately hard rock outcrops which rise to heights of a foot or more above the surface. Hammering of rocks which are lower than one foot necessitates the spacesuited subject to assume an extremely fatiguing and precarious semi-squatting or semi-kneeling position. Excessive strains are placed on the spacesuit when these positions are assumed. These precarious hammering positions would undoubtedly be even more difficult to assume under a 1/6-G condition where the astronaut's stability will be marginal.

Modification of the handle on one of the geological picks resulted in some improvement in the subject's ability to grasp the tool. This particular handle was designed to accurately mate with the irregular contours of the current Apollo spacesuit glove.

The problem of sample retrieval will be present regardless of whether a power tool or hand tool is employed to detach the rock specimen. One of the two subjects was capable (with difficulty) of retrieving a rock sample from the surface. The second subject could not reach closer than three or four inches to the standing surface. A potential approach for a sample retriever is presented in a later section of this report.

In summary, four major problems are encountered by the spacesuited subject when hammering or chipping rock specimens:

1. It is difficult to deliver a large number of hammer blows with sufficient energy to fracture specimens from the hard rock materials. The softer materials such as pumice are easier to sample, and a simple hatchet-type tool was found to be effective for this purpose.

2. When hammering, the subject must stand (or semi-kneel) relatively close to the rock outcrop as dictated by the reaching limitations of the

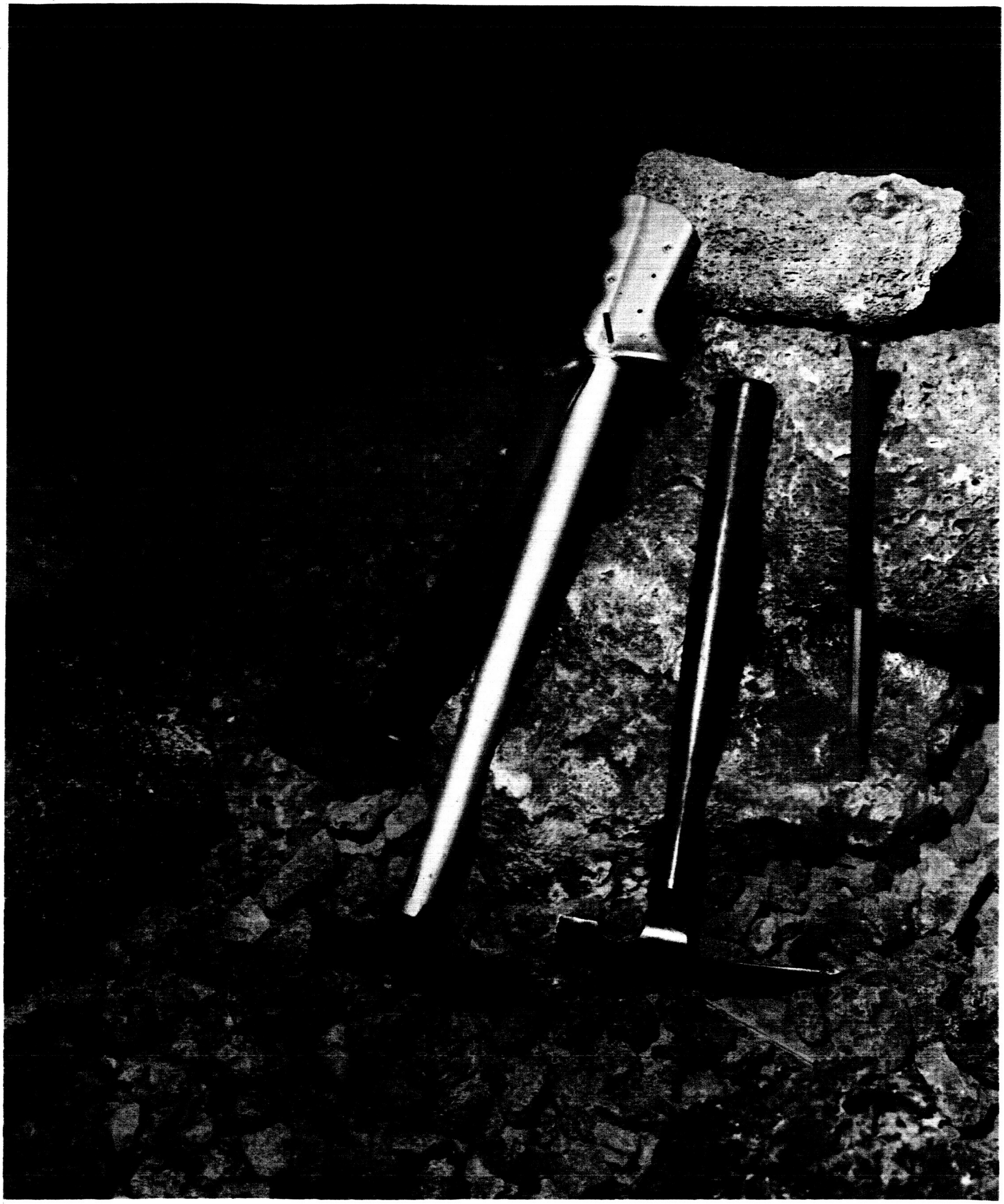

Figure 16. Standard Geological Sampling Tools

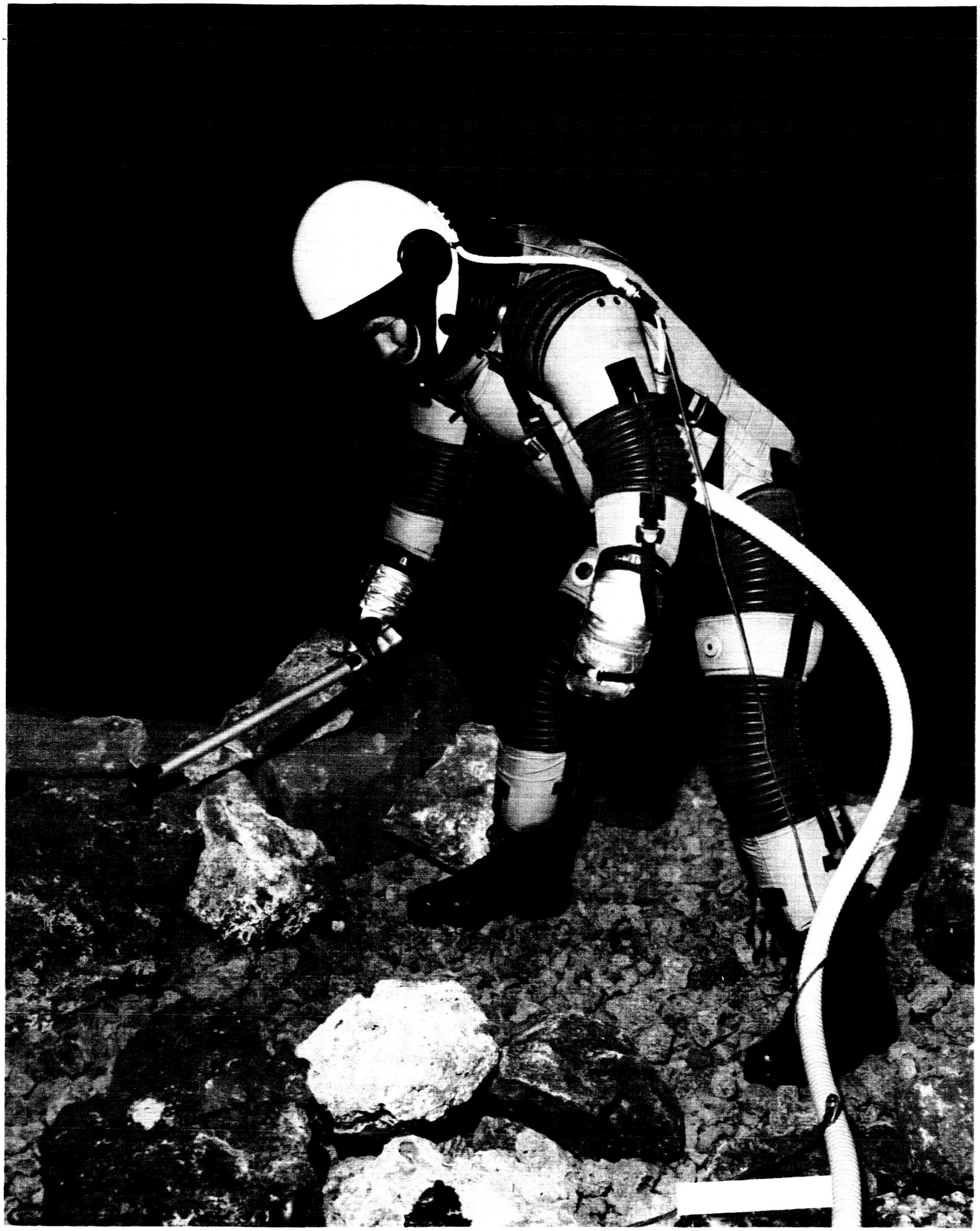

Figure 17. Modified Geological Sampling Pick

suit. Since it is difficult to firmly grasp the sampling pick, there is a continuous danger of a deflected blow hitting the subject. This problem will possibly be alleviated somewhat by the improved handle design.

3. Chipping debris from hard rock hammering is difficult to control. However, the debris problem is not serious when obtaining samples from softer materials such as pumice.

4. Hammering of rocks at "boot level" is extremely difficult. Increasing the handle length of the tool may alleviate this problem somewhat, but the restrictions of the suit will probably prohibit a "two-handed" operation.

Sample Weighing Device

The primary objectives of the sample weighing device tests were to evaluate the interface problems with the spacesuited subject, and to determine if the required $\pm$ 1 pound scale accuracy can be achieved using this technique.

Figure 18 illustrates a mockup of the sample weighing device. The mockup was fabricated to the specification outlined in the Potential Design Approaches section of this report. A twenty-inch length was assumed for the telescoping section (balance beam for scale) of the PLGT which was calibrated for weight tests in the low, medium, and high portion of the required 25-65 pound weighing range. Four precisely weighted canisters were employed to simulate the lunar weight of an assumed 16 pound PLGT battery (counterweight), and three rock boxes weighing 27, 48, and 63 pounds.

It was determined during the tests that the scale can be manipulated by the spacesuited subject without any major difficulties. Scale readability must be improved on the final device, and a means must be provided to prevent droppage of the scale beam from the suspended fulcrum. The required $\pm$ 1 pound accuracy was easily attained with the 27 pound weight although the 48 and 63 pound box weighing accuracy was somewhat marginal. The high end accuracy can be improved somewhat on the final device by using two fulcrum positions - one for the 25-45 pound range and the second for the 45-65 pound range.

Geological Hand Lens

Utilization of a standard geological hand lens by a spacesuited subject is an extremely difficult task. As illustrated in Figure 19, the device is small and the various fold-out lenses are difficult to grasp with the pressurized spacesuit glove. However, this problem can be easily corrected by mounting the lenses on a single handle which is designed to interface properly with the glove.

Figure 18. Sample Weighing Device

Figure 19. Geological Hand Lens

The optical interface problem between the hand lens and the helmet visor of the spacesuited subject is not too serious. The major difficulty encountered when holding the magnifier in front of the visor (approximately 2.5 inches from the eye) rather than at the normal position of 0.5 inches is a reduction in the field of vision. Use of a simple scale revealed a reduction of visual field of approximately one-half at a lens-to-eye distance of 2.5 inches as compared to 0.5 inches. There were no focusing problems encountered, although visual aberration becomes a problem at the higher magnifications. It is therefore recommended that the hand lens provided for the spacesuited astronauts be limited to the 3-12 magnification power range.

Rotary Percussion Drilling Tests

A commercial rotary percussion drill is being utilized for the feasibility penetration tests as illustrated in Figure 20. The purpose of these tests is to evaluate various types of rotary percussive bits which may be adaptable for coring, and to obtain corresponding power consumption data. Figure 21 illustrates a typical carbide bit and core samples which were obtained with the commercial rotary percussion drill. The rotary percussive action tends to fracture the core samples, but this can be alleviated by maintaining a relatively large diameter core (approximately one inch) and by reducing the coring bit kerf to the smallest possible thickness. A variable impact mechanism will be employed in the PLGT which will enable the astronaut to reduce the impacting energy when coring in the softer materials such as pumice.

Extrapolation of the penetration rate data obtained during the feasibility tests was used to predict the coring performance of the PLGT. The power required for continuous coring will greatly exceed that required for intermittent chipping or hammering. Table 2 lists the predicted number of 4-inch long (1 inch diameter) cores which can be drilled in a one-hour period for five types of materials.

Material	Power Expend.	Number of Cores Per Hour (4" x 1" Diameter)
Consolidated Basalt	500 watts	5
Slightly Vesicular Basalt	500 watts	14
Moderately Vesicular Basalt	500 watts	38
Obsidian	500 watts	12
Granite	500 watts	5

Table 2. Predicted Coring Penetration Rates for the PLGT

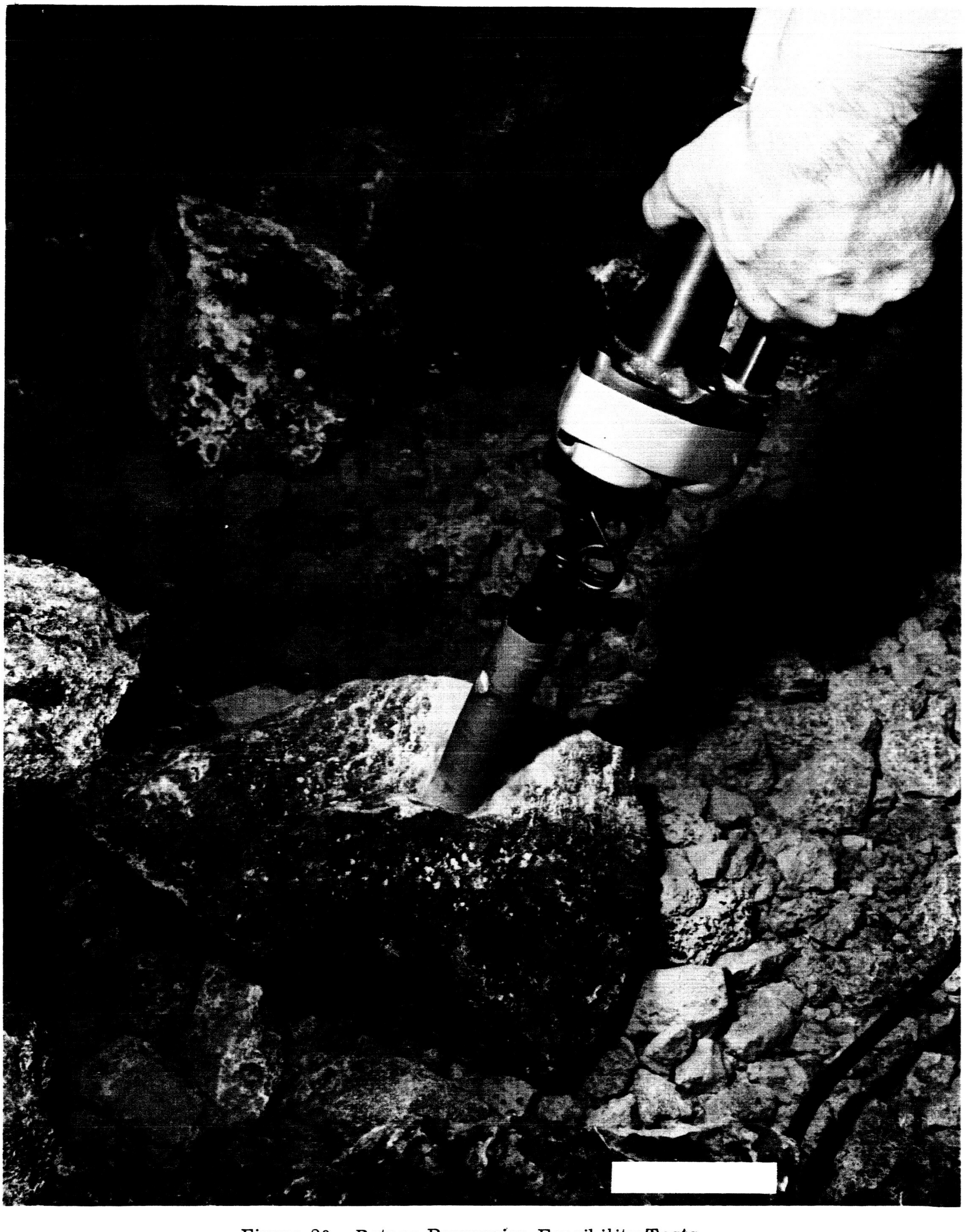

Figure 20. Rotary Percussion Feasibility Tests

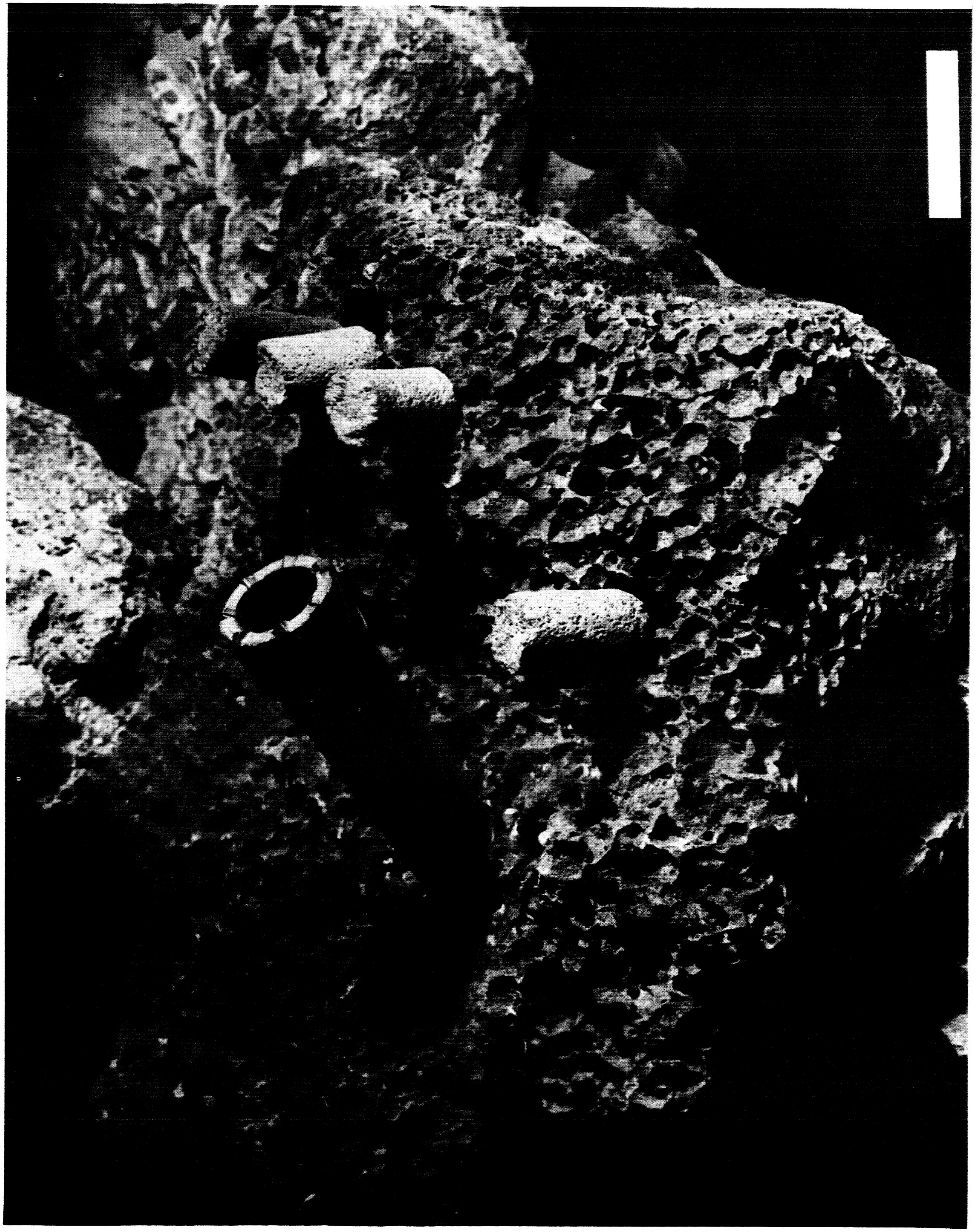

Figure 21. Carbide Bit and Core Samples

Sample Retriever

Figure 22 illustrates the use of a commercial device for retrieving small rock samples from the standing surface. The device, which is easily operated by the spacesuited subject with one hand, consists of four "claws" which automatically extend and open from one end of the thirty-inch rod when the spring-loaded operating button is depressed at the other end. When the operating button is released, the claws retract and close around the selected rock sample. The sample can subsequently be lifted and deposited in the desired location by again depressing the retriever operating button.

A mechanically operated retriever similar to the previously described device is currently being studied for possible inclusion in the lunar geological tool kit.

Optical Surveying Transit

An optical interface test was conducted to study the problems involved in the use of an alidade-type surveying instrument by a spacesuited subject. A standard Keuffel & Esser transit (See Figure 23) with a fixed ratio 1:100 stadia reticule possesses two horizontal stadia lines which will intersect a linear segment of a standard ranging pole equal to one-hundredth of the horizontal distance between the transit and the pole.

The major optical problem encountered with the transit was a reduction in the field of view resulting from the increased eye-to-lens distance through the spacesuit visor. Measurements obtained from the standard ranging pole revealed that a 1:4 reduction in the horizontal and vertical fields of view resulted when reading through the spacesuit helmet visor. The reduced visual field prevented simultaneous sighting of the upper and lower horizontal reticule stadia lines. However, this problem was easily overcome by slight movements of the head in a vertical plane such that the intersection of the upper and lower stadia marks with the ranging pole could be read during two independent measurements. This problem can also be alleviated by the use of a special-design eyepiece.

Utilization of the relatively sophisticated alidade by the lunar astronaut must be evaluated in terms of weight penalty and accuracy requirements. The weight of an alidade would probably be about four to five pounds. Alidade range measuring accuracy of approximately 1% or less must be compared with an instrument such as the STAPEL which possesses a lower degress of accuracy (approximately 10%) with a corresponding lighter weight of approximately one pound or less.

STAPEL

A feasibility model of the stadiametric portion of the previously described STAPEL was fabricated as shown in Figure 24. The device was tested on an outdoor course using a measured 20-foot section of vertical wall as the calibrated

Figure 22. Sample Retriever

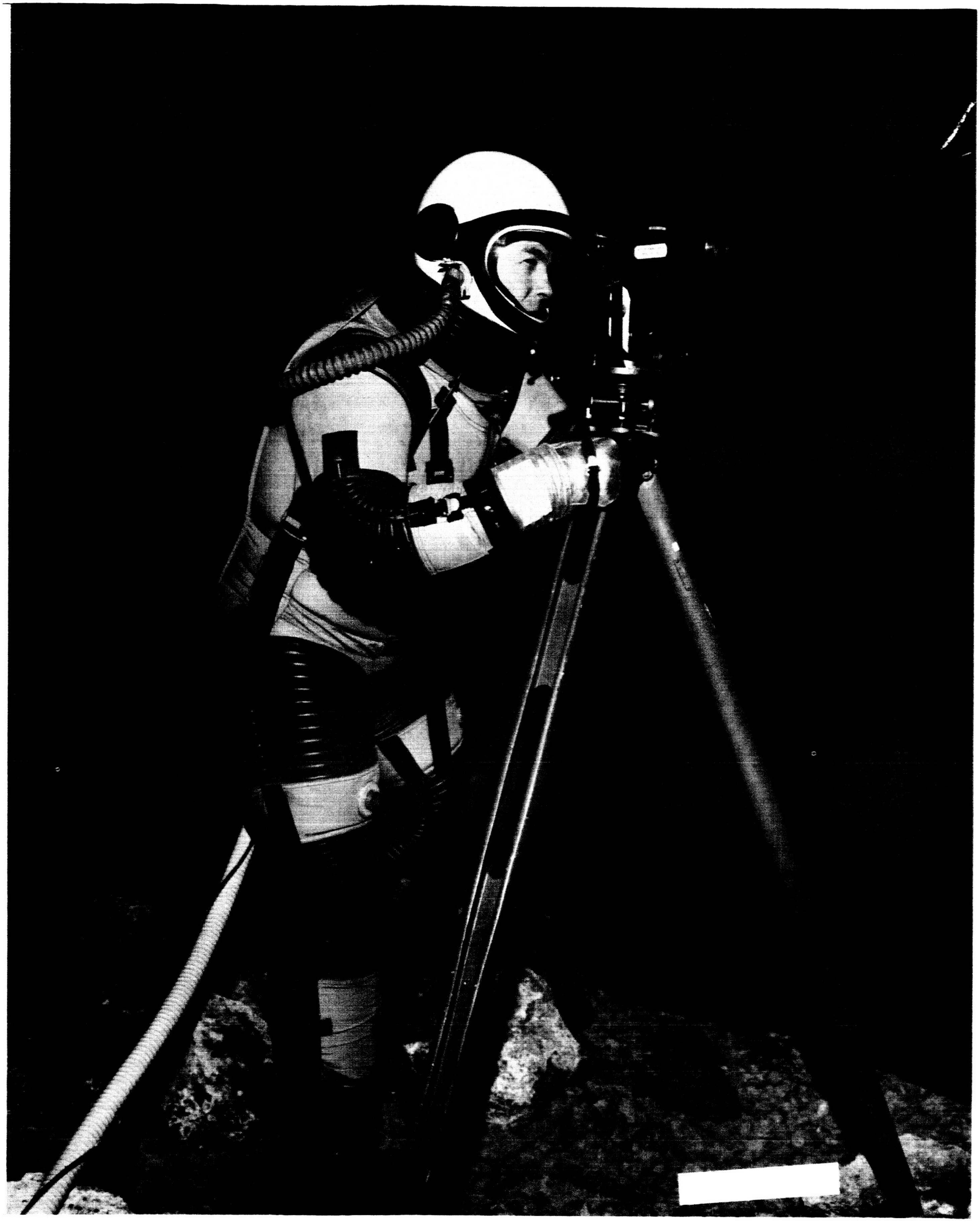

Figure 23. Surveying Transit - Spacesuit Interface Tests

Figure 24. STAPEL - Spacesuit Interface Tests

reference. Independent STAPEL measurements were made by two subjects at random horizontal distances from the vertical reference. The random points were subsequently surveyed with an optical stadia in order to determine the STAPEL accuracy at the random survey points. The results of this test are listed in Table 3.

Survey Point	STAPEL Measurement		True Measured Distance	Maximum STAPEL Error
	Observer #1	Observer #2		
#1	142 ft.	145 ft.	145 ft.	-2.06%
#2	320 ft.	310 ft.	317 ft.	-2.26%
#3	510 ft.	520 ft.	542 ft.	-5.90%
#4	800 ft.	750 ft.	821 ft.	-8.64%
#5	950 ft.	900 ft.	982 ft.	-8.35%

Table 3. STAPEL Measurement Accuracy

Utilization of the STAPEL mockup presented no serious problems although naked eye focusing is somewhat difficult at the longer distances of 800-1000 feet. The resulting measurement accuracies obtained during the test closely approximated the range uncertainty predicted in Figure 7.

CONCLUSIONS AND RECOMMENDATIONS

Performance of the lunar surface geological task analysis has resulted in the detailed definition of the exploration tool requirements. Potential design approaches were studied, and feasibility tests were conducted as required in order to evaluate the selected approaches.

Fabrication of the PLGT is currently in progress, and the device is approximately 80% completed Upon completion, extensive rock coring and chipping tests will be conducted in order to assure satisfactory operation of the basic mechanisms. Power consumption and penetration rate tests will be performed in order to evaluate the capabilities of the PLGT. Design modifications will be performed where required in order to optimize the operating characteristics of the device.

Detail design and fabrication of the PLGT surveying platform and clinometers is currently in progress. Design of the other auxiliary tools will be completed during the next report period.

Coordination with NASA will be required for selection of some of the potential design approaches such as the surveying instrument and sample weighing device.

Appendix A - Computation of True Lunar Bearing from STAPEL Measurements

The true lunar reference system bearing angle β of the LEM vehicle from the roving astronaut can be computed in the following manner.

Consider positions on the celestial sphere as given in terms of direction cosines (i. e., the components of a unit vector pointing to the position):

$$(1) \qquad \vec{u} = a\vec{i} + b\vec{j} + c\vec{k} \qquad (a^2 + b^2 + c^2 = 1)$$

For simplification assume a lunar equatorial coordinate system such that $\vec{i}$ and $\vec{j}$ lie in the moon's equatorial plane ($\vec{i}$ points to the lunar "vernal equinox") and $\vec{k}$ lies along the spin axis in the positive north direction. Thus, the spin axis vector is:

$$(2) \qquad \vec{u}_a = o\vec{i} + o\vec{j} + \vec{k}$$

and is fixed. The LEM position on the celestial sphere as viewed from the center of the moon is:

$$(3) \qquad \vec{u}_1 = \cos\lambda \cos(\phi + \Omega)\,\vec{i} + \cos\lambda \sin(\phi + \Omega)\,\vec{j} + \sin\lambda\,\vec{k}$$

where λ = lunar latitude

ϕ = lunar longitude

Ω = right ascension of the zero meridan. Ω is a known function of time and indicates the rotational orientation of the moon about its spin axis.

The leveling of the STAPEL aligns the pivot axis with the local vertical or with $\vec{u}_1$. The marking of time fixes an orientation of the $\vec{u}_1$ vector in the celestial sphere. Thus, at this time, there is a well defined geometric relationship between the planes formed by $\vec{u}_a$, $\vec{u}_1$ and by $\vec{u}_s$, $\vec{u}_1$. ($\vec{u}_s$ is the position of the sighted star.) The angle α between these planes gives the instantaneous azimuth from lunar true north (defined by $\vec{u}_a$, $\vec{u}_1$) to the trace of the star-local vertical plane (defined by $\vec{u}_s$, $\vec{u}_l$). This angle is easily computed as the angle between the normals to the planes:

$$\text{(4)} \qquad \cos \alpha = \frac{\vec{u}_a \times \vec{u}_l}{\left|\vec{u}_a \times \vec{u}_l\right|} \cdot \frac{\vec{u}_s \times \vec{u}_l}{\left|\vec{u}_s \times \vec{u}_l\right|}$$

By equations (1), (2), (3), it can be seen that:

$$\vec{u}_a \times \vec{u}_l = -\cos\lambda \sin(\phi + \Omega)\,\vec{i} + \cos\lambda\cos(\phi+\Omega)\,\vec{j} + o\vec{k}$$

$$\begin{aligned}\vec{u}_s \times \vec{u}_l = {} & \left[b_s \sin\lambda - c_s \cos\lambda \sin(\phi+\Omega)\right]\vec{i} \\ & + \left[c_s \cos\lambda\cos(\phi+\Omega) - a_s \sin\lambda\right]\vec{j} \\ & + \left[a_s \cos\lambda \sin(\phi+\Omega)\right. \\ & \quad \left. - b_s \cos\lambda\cos(\phi+\Omega)\right]\vec{k}\end{aligned}$$

The magnitude of the first vector product is simply $\cos\lambda$, hence the normalized vector is given by:

$$\frac{\vec{u}_a \times \vec{u}_l}{\left|\vec{u}_a \times \vec{u}_l\right|} = -\sin(\phi+\Omega)\,\vec{i} + \cos(\phi+\Omega)\,\vec{j} + o\vec{k}$$

Denote: $\vec{u}_s \times \vec{u}_l = a_{sl}\,\vec{i} + b_{sl}\,\vec{j} + c_{sl}\,\vec{k}$

Equation (4) can then be written:

$$\text{(5)} \qquad \cos\alpha = \frac{-a_{sl}\sin(\phi+\Omega) + b_{sl}\cos(\phi+\Omega)}{(a_{sl}^2 + b_{sl}^2 + c_{sl}^2)^{1/2}}$$

Where:

$$a_{sl} = b_s \sin\lambda - c_s \cos\lambda\sin(\phi+\Omega)$$

$$b_{sl} = c_s \cos\lambda\cos(\phi+\Omega) - a_s \sin$$

$$c_{sl} = \cos\lambda\left[a_s \sin(\phi+\Omega) - b_s\cos(\phi+\Omega)\right]$$

The value of α is computed by computing the arc cosine of equation (5). The principle value, $0 \leq$ P. V. $\leq 180^{\circ}$, is taken for α when $c_{sl} \leq 0$. When $c_{sl} > 0$, α is given by:

$$\alpha = 360^{\circ} - \text{P. V.}$$

It is only necessary to measure the time and identify the star (a_s, b_s, c_s) to perform the calculations for α. The procedure for computing the final bearing angle β relative to lunar true north is given by:

$$\beta = \alpha + \beta_l - \beta_s$$

The angle β gives the bearing of the line from the astronaut to the LEM. If the bearing from the LEM to the astronaut is desired, 180° must be added to β.